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ЕРЕВАНСКИЙ ФИЗИЧЕСКИЙ ИНСТИТУТ

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EXOTIC BARYON RESONANCES. MODERN STATUS. POSSIBILITIES TO SEARCH AND INVESTIGATE

ЦНИИатоминформ

ЕРЕВАН-1985

1. Introduction.

The problem of the exotic (multiquark) resonances existence is of particular importance for understanding the hadron physics.

It was supposed for a long time that there exist only nonexotic particles and resonances which can be composed of quark and antiquark $q\bar{q}$ (for bosons) and three quarks qqq (for baryons).

At the same time, the existence of the exotic resonances is predicted in a variety of theoretical schemes, such as the strong coupling model [1-3] , the Chew-Low bootstrap model [4] , the bag models [5-7] , the string models [8] , the dual approach [9,10] , the dispersion sum rules for reggeon-particle scattering [11-13] , the soliton model of baryons [14] . Being an inherent part of the cited schemes, the problem of the exotic states may turn out crucial for the verification of the adequacy of the theoretical representations which are the basis of one or another model.

All that points out the necessity of the investigation of the multiquark states, in particular the exotic baryon resonances*).

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*) Note that in the modern terminology, together with the multiquark resonances, those composed of gluons and/or quark-gluon mixture are also referred to the exotic resonances. We consider the baryons which have the "open" exotic quantum numbers of isospin, e.g. non-strange baryons with isospin $I=5/2$ and hyperons with strangeness $S=-1$ and $I=2$. They must consist at least of four quarks and one antiquark.

Unfortunately, the present experimental situation with these states does not seem very convincing. There are certain experimental evidences for the existence of baryons with I=5/2 in the $p\pi^+\pi^+$ and $n\pi^-\pi^-$ systems; however these experiments being performed mainly with the bubble chambers are poor in statistics, and they cannot be considered as strong evidence for the existence of the exotic baryons. It is obvious that a more careful analysis of these states in experiments with large statistics is needed.

Further, all the experiments are performed with the low-energy beams ($P_{lab} \lesssim$ 5.5 GeV/c) at which the contribution of the background subprocesses to the investigated system prevails over the resonance one. A substantial increase in the initial energies, up to SPS beam energies, is required to reduce the contribution of those subprocesses.

The aim of the present work is to ground the most favourable reactions and kinematical regions where an effective search for the exotic baryons is possible. The contribution of the background subprocesses to the investigated systems in various reactions and momenta configurations of the observed particles, as well as the dependence of these subprocesses on the incident particles energies is discussed.

Sect. 2 represents a short review of the theoretical approaches where the exotic baryon resonances are predicted. The features of the exotic resonances which follow from the sum rules for the reggeon-particle scattering amplitudes are given.

A number of experiments were performed since the early 60-ies to search for the resonances in the isospin I=5/2 $p\pi^+\pi^+$ and $n\pi^-\pi^-$ systems produced in the reactions on various beams and targets. The results of these experiments are briefly reviewed in Sect. 3.

As the processes of exotic state production proceed with small cross sections, the choice of the optimum reactions and measurement regimes is highly important to investigate effectively these states. These questions are considered in Sects 4-6.

Sect. 4 deals with the $p\pi^+\pi^+$-system produced in the exclusive $pp \to p\pi^+\pi^+\pi^-\pi^-p$ and $\pi^+p \to \pi^-\pi^+\pi^+p$ - processes in the proton fragmentation region. The background subprocesses are analysed which might be reflected kinematically into the $p\pi^+\pi^+$-system, thus embarrasing the observation of the resonances in this system. On the basis of this analysis, the kinematical restrictions which must be imposed on the detected particles momenta to reduce the contribution of the background subprocesses are determined.

It is interesting to observe the fast-flying $p\pi^+\pi^+$ system produced on π^+-beams. In this reaction the influence of the background processes is small, so the effective investigation of the resonances is possible.

In Sect. 5 the exclusive $\pi^+p \to p\pi^+\pi^+\pi^-$ reaction is analysed. Using the results of Ref. [11] the theoretical estimations of the cross sections of the exotic baryons produced in this reaction are given. These estimations show that the optimum π^+-beam energies at which the cross section of exotic baryon exclusive production is not too small are of the order of 20-90 GeV. At higher energies one can increase the cross sections considering the inclusive production of $p\pi^+\pi^+$-system which has a scaling nature.

In Sect. 6 the question of effective searching for the exotic resonances in the processes of inclusive production is discussed.

Together with the non-strange baryons there must exist the exotic ones with strangeness S=-1, -2, -3 (see Sect. 2). To search for the exotic hyperons with S=-1 strangeness, one should investigate the systems $\Lambda\pi^\pm\pi^\pm$ and $\Sigma^\pm\pi^\pm$. Sect. 7 deals with the problem of searching for baryons in these systems as well as for the exotic hyperons with S=-2 and -3.

To determine the resonance spin and parity, the angular distributions of the decay products should be analysed. In Sect. 8 we give the model-independent theoretical predictions for the angular correlations between the decay products for various combinations of the resonance spin and parity.

There exists an interesting possibility to investigate the exotic baryon

Regge trajectories by observing the inclusive production of $\Delta^{++}(1232)$ and Σ^{+}-resonances in the π^{-}-beams fragmentation region. This question is elucidated in Sect. 9.

As was already mentioned, the cross sections of the exotic baryons production constitute a very small part of the main processes. To investigate these baryons, one needs the installations, which have a high efficiency in the particles registration in the wide kinematical region. In Sect. 10 the efficiency of an OMEGA-type spectrometer in the investigation of the exotic baryons is considered. The expected number of the experimental events for these baryons production is calculated. The calculations show that this number should exceed at least by two orders of magnitude the total statistics up to now accumulated. It is shown that the OMEGA spectrometer allows one to carry out measurements over the whole required region of initial energies and kinematical configurations of the reactions products. Of great importance is the conclusion that these measurements demand no changes in the construction of OMEGA.

2. Theoretical Outlook.

The isospin $I \geqslant 5/2$ baryon states appeared for the first time in the work of G. Wentzel in 1940 [1] (see also [2]). The interaction of the nucleon source with surrounding meson field was considered. From the solution of the quantum-mechanical problem on the energy eigenvalues for the nucleon + pions system it was shown that at a large coupling constant there arise the excited states with isospin $I=3/2, 5/2, \ldots.$ Within the analogous approach W. Pauli and S. Dancoff [3] took into account also the pion field angular momentum. This gives rise to the correlation between spin and isospin of the excited states: $J \geqslant I=1/2, 3/2, 5/2, \ldots.$ Discovered in the early fifties, the $\Delta_{33}(1232)$-resonance became a striking confirmation of the strong coupling theory predictions.

The exotic baryons appear as natural components also in the models based on more contemporary approaches to the investigation of the dynamics of strong interactions, such as the dispersion relations, QCD, etc.

So, a series of the I=J baryon states, whose first terms are the nucleon and the Δ (1232)-isobar, are predicted [4] in the Chew-Low static bootstrap model based on the dispersion relations and crossing-symmetry.

The baryon states with $qqq+n(q\bar{q})$ quark contents arise at the self-consistent dual amplitudes construction [9,10] .

The idea of the colour confinement leads to the representations of hadrons as bags consisting of quarks and also as chromodynamics strings. Within these representations the exotic baryon resonances are also expected [5-8].

The hypothesis of a soliton nature of baryons is widely spread now [14]. The baryons are treated as soliton solutions of the effective lagrangian which corresponds to the low-energy limit (the soft-pion limit) of the current algebra. A series of baryon resonances with I=J=1/2, 3/2, 5/2,... is also predicted in this approach.

One of the theoretical approaches where the properties of the predicted states obtain a rather quantitative description is that based on the dispersion sum rules for the reggeon-particle scattering amplitudes (αa -amplitudes). A good agreement of the αa -amplitude sum rules predictions with the experimentally measured characteristics of the processes involving the ordinary hadrons [15] shows the large possibilities of this approach. In particular, it predicts the correct value of the Δ (1232) $\rightarrow N\pi$ decay width , the ratiosof the binary processes cross sections, the spin structure in the vertices of the different reggeon couplings with N and Δ_{33} - baryons.

The successive application of sum rules leads to the prediction of $I \geq 5/2$ exotic baryons existence. The sum rules allow one to determine unambiguously the spin and parity of these baryons (J=I, P=+). Thus we see that the existence of the exotic baryon resonances is predicted in quite different theoretical approaches. As to the properties of these resonances - spins, particles, masses, decay modes and widths - the theoretical predictions either are absent in some approaches or represent a highly motley scale of possibilities. From this viewpoint, the agreement between the strong coupling theory, bootstrap and soliton models and sum rules for the αQ -amplitudes seems very intriguing. Probably, such agreement points out a closer relationship between these approaches.

Consider now the properties of the I=J=5/2 state called in [11] E_{55} - resonance.

E_{55} -baryon is an analog of N and Δ_{33} in the world of I=5/2 resonances - the ground state among these resonances. The most probable decay mode of E_{55} is the cascade process $E_{55} \to \Delta_{33}\pi \to N\pi\pi$. At small momenta of the decay $E_{55} \to \Delta_{33}\pi$ for the width Γ_E a simple formula is predicted [11] :

$$\Gamma_E = \frac{|\vec{p}_\Delta|^3 \; M_\Delta}{4\pi S_0 \; M_E} \left(G^{p\pi^0 p}\right)^2 \tag{2.1}$$

where $\vec{p}_\Delta$ is the decay momentum, S_0 = 1 GeV^2.

The values of Γ_E at different M_E are given in Table 2.1.

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

If the E_{55}- mass is less than 1.5 GeV, then Γ_E is rather small. In this case an extraction of the resonance peak from the background is possible. At $M_E \gtrsim$ 1.6 GeV the resonance discrimination may turn out very complicated *).

Together with the non-strange baryons there must exist the exotic ones with strangeness S=-1, -2, -3. E.g., from the sum rules for $\alpha\alpha$ -amplitudes it follows [13] the existence of two resonances with S=-1 and I=2 - $S_E^*(J_{S_E^*}=5/2;\ P_{S_E^*}=+)$ and $S_E(J_{S_E}=3/2;\ P_{S_E}=+)$.

S_E^* -resonance is the strange analog of E_{55} -baryon. The decay into $\Sigma^*(1385)\pi$ channel is expected to be dominant for S_E^* -hyperon. At small decay momenta, for the width $S_E^* \to \Sigma^*(1385)\pi$ -decay the following formula is predicted:

$$\Gamma_{S_E^* \to \Sigma^*\pi} = \frac{|\vec{p}_{\Sigma^*}|^3\ M_{\Sigma^*}}{6\pi S_0\ M_{S_E^*}}\left(G^{S_E^*\pi\Sigma^*}\right)^2. \qquad (2.2)$$

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

S_E- hyperon can decay both into $\Sigma\pi$- and $\Sigma^*(1385)\pi$ -channels. The corresponding partial decay widths are predicted to be

$$\Gamma_{S_E \to \Sigma\pi} = \frac{|\vec{p}_\Sigma|^3(E_\Sigma + M_\Sigma)}{12\pi S_0\ M_{S_E}}\left(G^{S_E\pi\Sigma}\right)^2 \qquad (2.3)$$

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

and

$$\Gamma_{S_E \to \Sigma^*\pi} = \frac{5\ |\vec{p}_{\Sigma^*}|^3}{72\pi M_{S_E} M_{\Sigma^*}}\left(G^{S_E\pi\Sigma^*}\right)^2 \qquad (2.4)$$

where $\left(G^{S_E\pi\Sigma^*}\big/G^{\Sigma^*\pi\Lambda}\right)^2 = 18/25$

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*) Recently, there appeared certain experimental evidence for the existence of the state with ≈ 1.44 GeV mass in the $p\pi^+\pi^+$ and $n\pi^-\pi^-$ systems. This state decays mainly into the $\Delta_{33}\pi$ channel, its decay width is in good agreement with formula (2.1), and the angular distributions of the decay products do not contradict J = 5/2 and P = + (see Sect. 3).

Tables 2.2 and 2.3 list the values of $\Gamma_{S_E^* \to \Sigma^*\pi}$ and $\Gamma_{S_E \to b\pi}$ at various masses.

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	171	250

Table 2.3

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

One can see from Table 2.2 that the effective search for the S_E^* - resonance can be carried out in the $\Sigma^*(1385)\pi$ -system at masses $\lesssim$ 1.75 GeV. At larger masses it will be difficult to discriminate the S_E^* -resonance because of its large width.

As to the S_E -resonance, one can see from Table 2.3 that it should be searched for in the mass region $\lesssim$ 1.60 GeV of the system $\Sigma\pi$. The search for S_E in the $\Sigma^*(1335)\pi$ - system seems extremely ineffective because of its weak coupling to this system.

Analogously, the resonance interaction in the exotic systems $\Xi\pi$ (I=3/2) and $\Omega^-\pi$ should be expected.

Resume of this section. One must investigate in detail the resonances in the $p\pi^+\pi^+$ -system mass distribution in the $M_{thr} < M(p\pi^+\pi^+) < 1.8$ GeV region. restricting the mass of the $p\pi^+$ subsystem to the Δ (1232) resonance region.

The exotic S = -1 baryons should be searched for in the $\Lambda\pi^\pm\pi^\pm$ - (with the extraction of the $\Sigma^*(1385)$-resonance region in the $\Lambda\pi$ subsystem) and also in the $\Sigma^\pm\pi^\pm$-systems in the $M_{thr} \div 1.8$ GeV mass interval.

To search for the exotic baryons with S = -2 and -3 one has to investigate, e.g. the systems $\Xi^-\pi^-$ and $\Xi^0\pi^+$; $\Xi^-\pi^-\pi^0$ and $\Xi^0\pi^-\pi^-$ (with the selection $\Xi^{*-}(1520)\pi^-$); $\Omega^-\pi$.

3. Experimental Status.

The present section contains a brief review of the experiments on baryon resonance search in the exotic systems $p\pi^+\pi^+$ and $n\pi^-\pi^-$.

The first experiments on investigation of the $p\pi^+\pi^+$ system were carried out in the early sixties. A few reports concerning this subject were contributed to the XII International Conference on High Energy Physics (Dubna, 1964). Among those reports, the work on studying the $\pi^+p \to \pi^-\pi^+\pi^+p$ reaction at $P_{lab} = 3.65$ GeV/c is of particular interest [16]. It was shown in this work that the peak in the $p\pi^+\pi^+$-system mass distribution at $M(p\pi^+\pi^+) \approx 1560$ MeV can be treated as a kinematical reflection of the $\pi^+p \to \rho^0(\to\pi^+\pi^-) + \Delta^{++}(\to p\pi^+)$ subprocess.

Later on, the I = 5/2 states were from time to time investigated by various groups. The results of those experiments are rather conflicting. So, in Ref. [17] a peak in the system $n\pi^-\pi^-$ at $M(n\pi^-\pi^-) \approx 1640$ MeV in the reaction $\pi^-d \to pn\pi^-\pi^-\pi^+$ at $P_{lab} = 2.26$ GeV/c was observed. In the same 1969. there was published the work [18] on studying the mass spectrum of the $p\pi^+\pi^+$-system produced in the reaction $\pi^+d \to np\pi^+\pi^+\pi^-$ at $P_{lab} = 1.1 \div 2.37$ GeV/c. The mass distribution does not reveal any distinct structure in the region $M(p\pi^+\pi^+) = 1500 + 2000$ MeV.

The $n\pi^-\pi^-$-system was studied in a series of K^--beam experiments in the reaction $K^-d \to \overline{K}^0 p\pi^+ n\pi^-\pi^-$, the incident momenta being 4.91 GeV/c [19], 5.5 GeV/c [20], 4.48 GeV/c [21]. It is claimed in Ref. [19] that a peak is observed at M ($n\pi^-\pi^-$) ≈ 1630 MeV, whereas the results of [20, 21] testify against this peak.

Note that the above-mentioned experiments were performed with the bubble chambers, so they are poor in statistics. The authors of [22] investigated the inclusive reaction $\pi^+ p \to \pi^- X^{+++}$ at P_{lab} = 1.9 GeV/c using a spark chamber. They claim that the X^{+++} mass distribution is described by the one-pion-exchange (OPE) model and reveals no resonance structures at $M_{X^{+++}} < 1750$ MeV. The same distribution at the π^+-meson momentum 3.88 GeV/c was studied by the authors of [23]. Within the experimental errors (pretty large) they observed no resonance peaks in the X^{+++} system in the $M_{X^{+++}}$ = 1.2 ÷ 2.2 GeV interval, and the observed distribution was explained as the kinematical reflections of the other subprocesses.

Recently, the systems with the exotic quantum numbers and particularly the I = 5/2 baryons have become attractive again.

The mass distribution in the $p\pi^+\pi^+$- and $n\pi^-\pi^-$- systems produced in the reaction $np \to n\pi^-\pi^- p\pi^+\pi^+$ at the monochromatic neutron momenta P_{lab} = 3.83, 4.35 and 5.10 GeV/c was studied at JINR [24,25]. On a level of 3-4 standard deviations at M ($N\pi\pi$) ≈ 1.44 GeV there was observed a resonance which decays mainly into the channel $\Delta_{33}\pi$. The experimental width of this state (Γ_{exp} = 23 ± 10 MeV) agrees well with the formula (2.1) predicted value (Γ_E ≈ 36 MeV at a mass E_{55} = 1.44 GeV), and the decay product angular distribution does not contradict the spin-parity values $5/2^+$. Ref. [26] reports the observation of the resonance with M ≈ 1.42 GeV in the $p\pi^+\pi^+$-system produced in the reaction $\pi^+ p \to \pi^+\pi^+\pi^-\pi^0 p$ at P_{lab} = 4.37 GeV/c. The width of this state (13 ± 7 MeV) also agrees with the theoretical one ($\Gamma_E \gtrsim$ 20 MeV; M_E = = 1.42 GeV). The authors of the latter work emphasize that this resonance is the decay product of the heavy Δ^{++} (1890)-isobar preliminarily produced in the $p\pi^+\pi^+\pi^-$-system.

Besides the above-quoted state, in the works [24-26] as well as in the other ITEP experiments [27, 28] different singularities were observed in the $p\pi^+\pi^+$- and $n\pi^-\pi^-$- systems with I = 5/2 at various masses: 1.52 and 1.89 GeV [25] ; 1.56 and 1.69 GeV [26] ; 2.76 and 2.15 GeV [27] ; 1.52, 1.74 and 1.99 GeV [28] . These experiments also were performed with the bubble chambers, this resulting in poor statistics.

Thus we see that the situation with searching for the resonances in the I = 5/2 $p\pi^+\pi^+$- and $n\pi^-\pi^-$- systems is highly complicated, this obviously demanding setting up the experiments with high statistics. Such experiments would appear a crucial check for the existence of the I = 5/2 baryon states.

Further, all the experiments performed up to now were carried out with low-energy beams ($\lesssim$ 5 GeV/c). At such energies, the reflections of the background processes give a large contribution to the investigated systems. To separate the kinematical regions where the contribution of these reflections is small, an essential increase in the beam energy is necessary (see Sect. 4).

4. Search for the Exotic Baryons in the Proton Fragmentation Region. The Kinematical Reflection Problem.

The basic problem arising in the investigation of resonance states in the mass spectra consists in a possibility to discriminate the resonance signal from the background. The question of the resonance signal discrimination becomes especially important in studying the exotic states which have small production cross section. The background processes can give a larger contribution to the investigated system, thus making the resonance observation impossible because of too small signal-background ratio. Moreover, the background processes may display themselves in the form of kinematical (non-resonant) peaks in the studied system. In this connection, it is highly important to determine correctly the kinematical regions where the contribution of background processes is small.

To illustrate what is said above, let us consider the system $p\pi^+\pi^+$ produced in the reaction

$$pp \rightarrow p\pi^+\pi^+\pi^-\pi^- p \qquad (4.1)$$

in the proton fragmentation region.

In our further analysis we shall use the one-pion-exchange (OPE) model which is successfully applied to describe the processes with ordinary hadrons.

Let the $p\pi^+\pi^+$-system be a product of E^{+++}- resonance decay ($E^{+++} \rightarrow \Delta^{++}\pi^+ \rightarrow p\pi^+\pi^+$). In the OPE model the diagram describing the E^{+++}- resonance production in the proton fragmentation region has the form shown in Fig. 4.1.

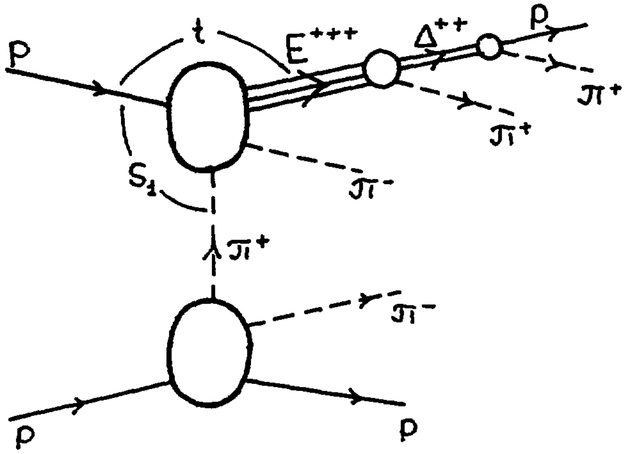


Fig. 4.1

Let us turn now to the background contribution. This contribution can be divided into two parts. A first part is a background connected with the dynamics of the non-resonant interactions in the $p\pi^+\pi^+$ $(\Delta^{++}\pi^+)$- system. A second part has a kinematical nature and is associated with the fact that the proton and π^+ -mesons (Δ^{++} and π^+ -meson) can be produced in the other subprocesses and contribute to the system under study.

What subprocesses of the reaction (4.1) can be reflected into the $p\pi^+\pi^+(\Delta^{++}\pi^+)$ – system?

Turn to Fig. 4.1. The upper block of the diagram describes the E^{+++} production process in the virtual π_v^+ -meson-proton scattering reaction. Therefore, it is obvious that the kinematical background in reaction (4.1) is closely connected with that in the reaction

$$\pi^+ p \to \pi^+\pi^+\pi^- p \qquad (4.2)$$

(As the virtual π -meson in the multiperipheral kinematics is not too far from the mass shell , one may consider the process of the real π -meson scattering).

As was already mentioned in Sect. 3, to the system $p\pi^+\pi^+(\Delta^{++}\pi^+)$ produced in the proton fragmentation region of reaction (4.2) a large contribution comes from the decay products of the $\pi^+ p \to V^0\Delta^{++}$ subprocesses, whose cross section is not small. As a result, the $p\pi^+\pi^+(\Delta^{++}\pi^+)$-system is produced mainly via the background subprocesses, this strongly complicating the resonance observation in this system.

How can one reduce the background subprocesses contribution?

Consider a diagram plotted in Fig. 4.2 and discuss the reflection

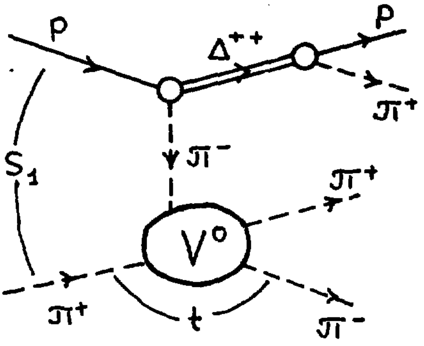


Fig. 4.2

of the process shown in this diagram to the given mass $M_{fix}(\Delta^{++}\pi^{+})$ of the $\Delta^{++}\pi^{+}$ – system at different S_1. It is obvious that with increasing S_1 the contribution to the given mass $M_{fix}(\Delta^{++}\pi^{+})$ is made by larger and larger values of the masses $M_{\pi^+\pi^-}$ at the bottom of the diagram. As to the small $M_{\pi^+\pi^-}$ mass reflection region, it shifts towards the large masses of the $\Delta^{++}\pi^{+}$ – system.

Fig. 4.3 presents the $\pi^+\pi^- \to \pi^-\pi^+$ – process cross section as a function of $M_{\pi^+\pi^-}$. In the large mass region this cross section is very small, since it is determined by the contribution of the t-channel ingularities with I = 2.

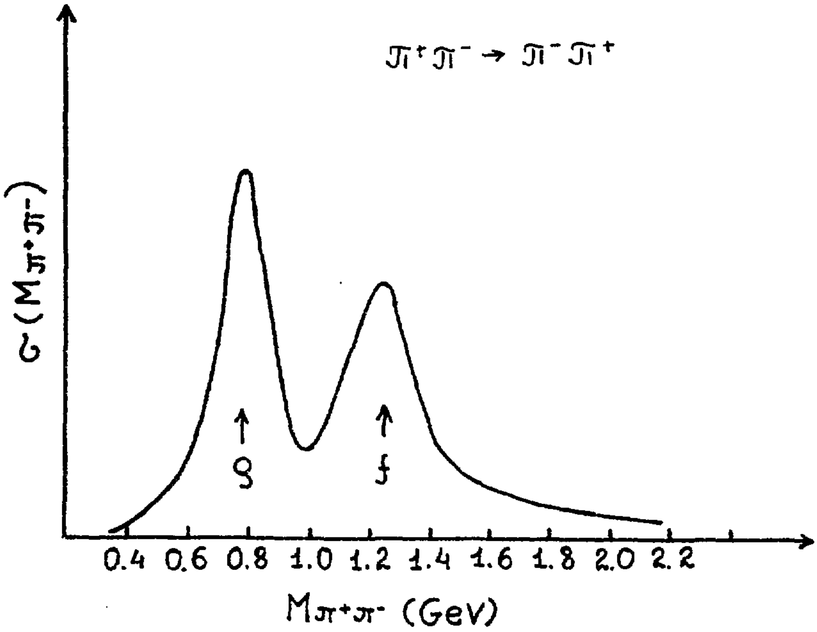


Fig. 4.3

In this region the cross sections of both the E^{+++} – resonance and non-resonant $\Delta^{++}\pi^{+}$ – system production should be of the same order, as they are determined by the t-channel exchange with $I_t = 2$ (see Fig.4.4 a,b). As for the region of small S_1 and $M_{\pi^+\pi^-}$, the non-resonant production of the $\Delta^{++}\pi^{+}$ – system via the mechanism shown in Fig. 4.2, dominates there.

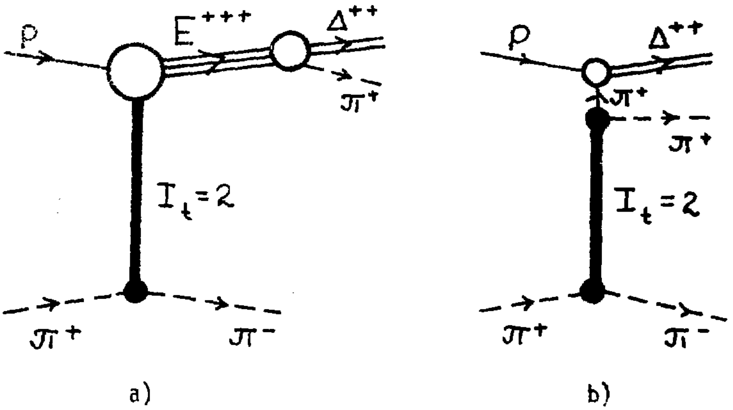


Fig. 4.4

Now turn back to the reaction (4.1) and consider the fast-flying system $\Delta^{++}\pi^+$. If we impose no additional conditions on the π^--meson momenta, then the diffractive production of the small mass of the $\Delta^{++}\pi^+\pi^-\pi^-$-system (and respectively of the small S_1 of the $\Delta^{++}\pi^+\pi^-$ system) dominates (see Fig. 4.5).

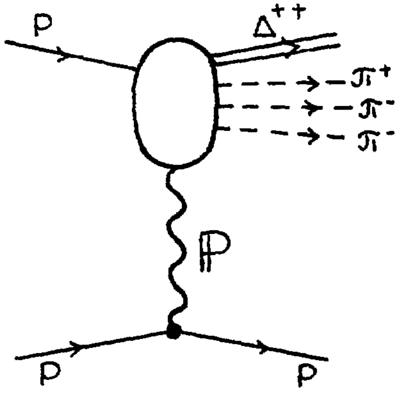


Fig. 4.5
($\mathbb{P}$ is the vacuum trajectory)

Therefore, even at very high energies of the incident proton, in the mass region $M_{thr} < M(\Delta^{++}\pi^+) <$ 1.8 GeV of the $\Delta^{++}\pi^+$- system one will observe a large background which imitates that at low initial energies.

Thus, for the effective observation of the exotic baryon resonances produced in the reaction (4.1) in the projectile proton fragmentation region, additional conditions, the π^- -mesons momenta in the lab. system to be sufficiently smaller than the π^+ -mesons ones, should be imposed.

Obviously, when searching for the exotic resonances in the target-proton fragmentation region in the reaction (4.1), these conditions are to be replaced by the inverse ones - the π^- -mesons momenta must be larger than the π^+ -mesons ones.

The positions of the peaks caused by the background subprocesses must depend on the momenta configurations. As distinct from the resonance peaks, these ones have to shift under the variation of the imposed kinematical constraints. In particular, the kinematical peaks in the $p\pi^+\pi^+$- system produced in reactions (4.1) and (4.2) must shift and vary in their shape at variation in the relation between the π^- -mesons and the $p\pi^+\pi^+$- system momenta (S_1 variation), and also between the π^-- and π^+ - mesons momenta ($M_{\pi^+\pi^-}$-variation).

At present, using the pion-exchange realistic model, the calculations of the contribution of the background subprocess shown in Fig. 4.2 to the $p\pi^+\pi^+(\Delta^{++}\pi^+)$-system mass distribution have been carrying out.

5. E^{+++} Observation in the Backward Production Processes on the π^+ -Beams.

The search for the E^{+++} -resonances in the fast-flying $p\pi^+\pi^+$ $(\Delta^{++}\pi^+)$-system produced in the π^+ -beam processes (the so-called backward production processes) seems to be most effective. Consider the exclusive reaction

$$\pi^+ p \rightarrow p\pi^+\pi^+\pi^- \tag{5.1}$$

in the kinematics where the $p\pi^+\pi^+$ - system flies in the π^+ -beam direction (the choice of such kinematics can be realized by a simple master-signal when π^- in the lab. system flies to the back hemisphere). The diagram describing this process corresponds to the exchange in the U - channel by the baryon Δ -pole (see Fig. 5.1).

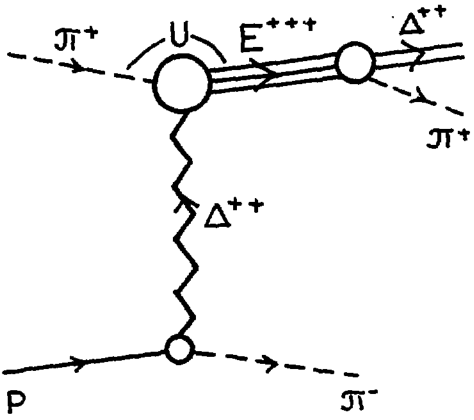


Fig. 5.1

Important in this kinematics is that the background processes which can reflect into the $\Delta^{++}\pi^+$- system also proceed via the baryon poles exchange. Owing to that, the ratio of the production probabilities for the background system and the resonance may be not as large as in the proton fragmentation region production. Fig. 5.2 shows a diagram of the $\pi^+p\to\Delta^{++}V^0$ background process similar to the diagram in Fig. 4.2.

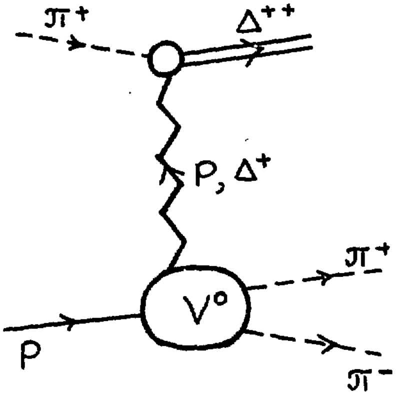


Fig. 5.2

There is a possibility to estimate the cross section which corresponds to the Fig. 5.1 diagram for the case of the E_{55} -resonance production. Let us consider the $\pi^- p$-backward scattering process (see Fig. 5.3).

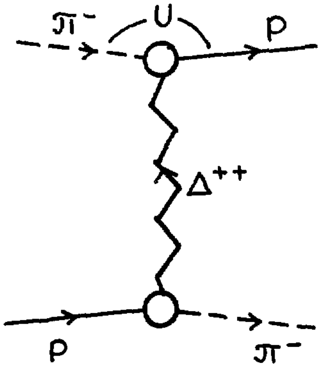


Fig. 5.3

We see that both the E_{55} -resonance production and the $\pi^- p$-backward scattering are determined by the Δ -Regge trajectory contribution. The $\mathcal{L}a$ -amplitude sum rules (see Sect. 2) predict a definite relation between the $N\pi\Delta$ - and $\Delta\pi E_{55}$ - vertices in case when N, Δ and E_{55} are on the mass shell.

Assuming that the formfactor of Δ which describes the off-mass shell effects is the same in both reactions, we can use the prediction of sum rules and get

$$\frac{d\sigma}{du}(\pi^+ p \to E_{55}^{+++}\pi^-) \Big/ \frac{d\sigma}{du}(\pi^- p \to p\pi^-) = \frac{2}{15}\,\varphi(u) \tag{5.2}$$

with
$$\varphi(u) = 1 - \frac{u}{M_E^2} + \frac{u^2}{M_E^4} \tag{5.3}$$

Fig. 5.4 presents the experimental data [29] on

$\frac{d\sigma}{du}(\pi^- p \to p\pi^-)\Big|_{u=0}$ as a function of initial momentum.

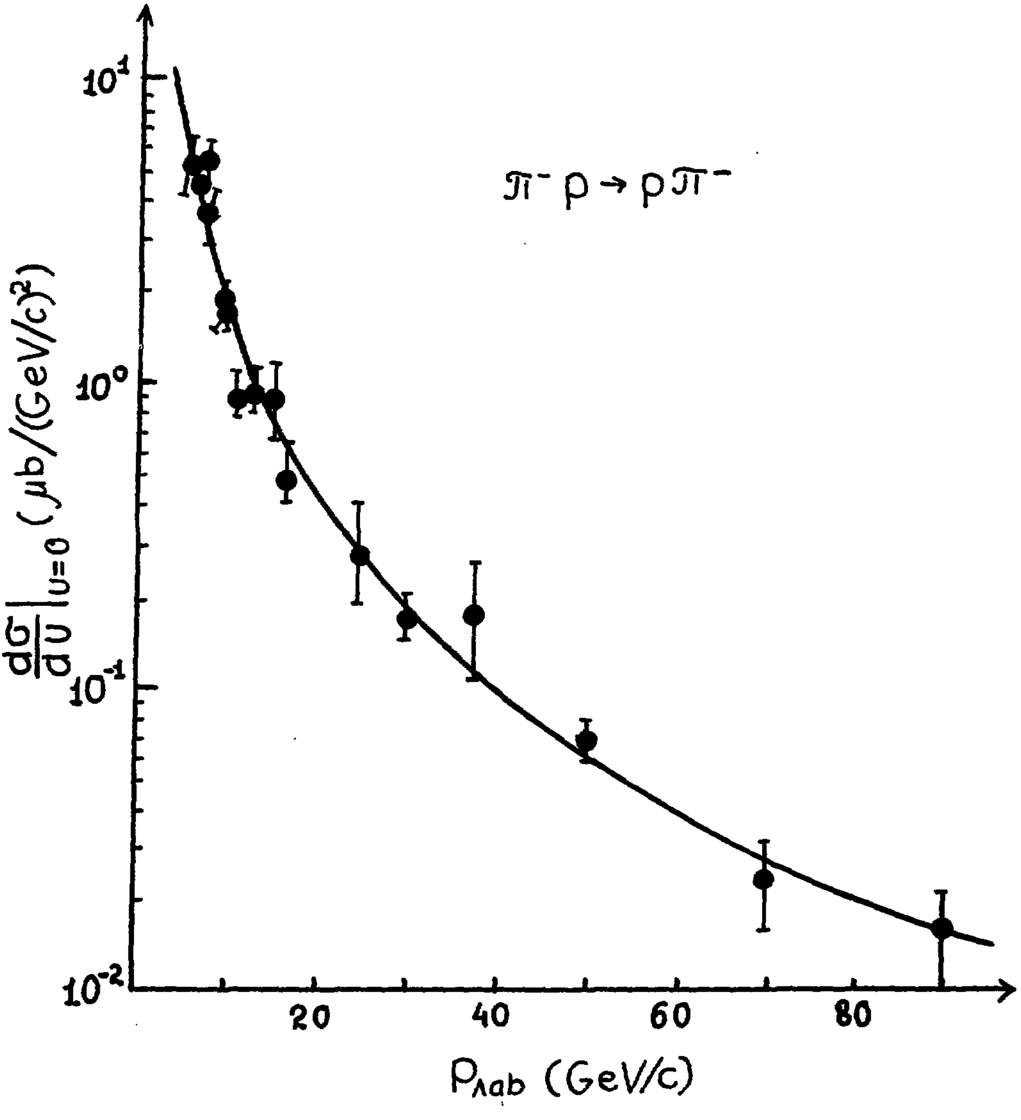


Fig. 5.4

The curve in Fig. 5.4 represents the experimental data parametrization in the form of $K\, p_{lab}^{-n}$ with $n = 2.08 \pm 0.06$ [29].

There exists an interesting possibility to search for the E^{+++} - resonances in reaction (4.1) at high energies at a special momenta configuration which imitates the backward scattering process. This configuration becomes apparent from the consideration of Fig. 5.5.

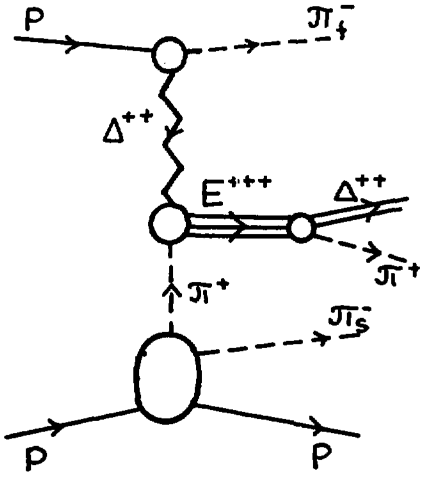


Fig. 5.5

The kinematical restrictions leading to the configuration described by the Fig. 5.5 diagram and enabling one to study effectively the E^{+++} - resonances have the following form in the lab. system:

$$p_{\pi_f^-} \gg p_{E^{+++}} \gg p_{\pi_s^-} \;\; ; \;\; p_{\pi_f^-} \gg p_{\pi_i^+} \gg p_{\pi_s^-} \, ,$$

$M_{\pi_f^-\Delta^{++}\pi^+} \approx M_{\pi_s^-\Delta^{++}\pi^+}$ are the large quantities (see the analysis in Sect. 4).

6. Search for the Exotic Baryons in the Inclusive Production Processes in the π - Beam Fragmentation Region.

An essential increase in the cross section of the fast system $p\pi^+\pi^+$ production in the processes with high-energy π^+ beams ($\gtrsim$ 100 GeV) can be achieved under the observation of the inclusive production of this system (see Fig. 6.1).

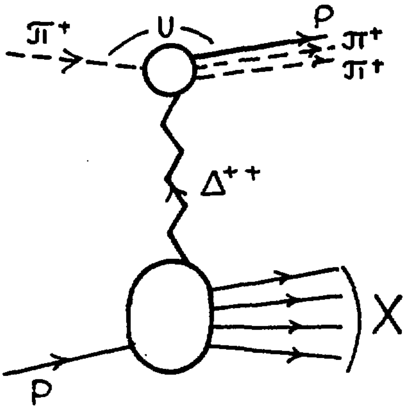


Fig. 6.1

Just as in Sect. 5, one can estimate theoretically the E_{55}^{+++} inclusive production cross section in the π^+ -beam fragmentation region:

$$\pi^+ p \to E_{55}^{+++} X \tag{6.1}$$

In the Δ -reggeon exchange model this cross section has the following form:

$$\frac{d\sigma^{\pi^+ \to E_{55}^{+++}}}{dx\,du} = (1-x)^{1-2\alpha_\Delta(u)} f_E(u)\, \sigma_{tot}^{\bar{\Delta}_v p}(M_x^2, u) \tag{6.2}$$

where x is a scaling variable (momentum fraction carried by E - baryon), $f_E(u)$ is Δ - reggeon formfactor, $\sigma_{tot}^{\bar{\Delta}_v p}(M_x^2, u)$ is total cross section of the scattering on the proton of the virtual Δ -resonance with mass u .

On the other hand, the cross section of the proton inclusive production in the π^- - beam fragmentation region

$$\pi^- p \to pX \tag{6.3}$$

which also is determined by the Δ -reggeon exchange (see Fig. 6.2) is as follows:

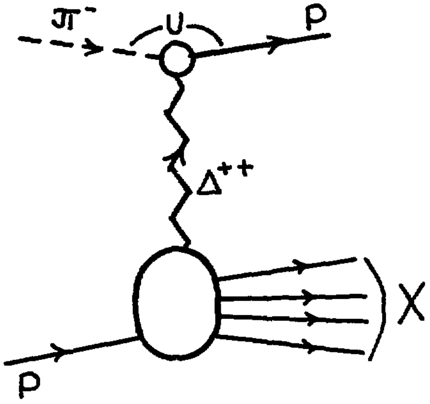


Fig. 6.2

$$\frac{d\sigma^{\pi^- \to p}}{dx\,du} = (1-x)^{1-2\,'_{\Delta}(u)} f_p(u)\,\sigma_{tot}^{\bar{\Delta}_v p}(M_x^2, u) \qquad (6.4)$$

where $f_p(u)$ is the corresponding Δ -reggeon formfactor. Just as for the exclusive production processes (see Sect. 5), assuming the formfactor of Δ is the same in the processes (6.1) and (6.3), one can get the relation between the cross sections (6.2) and (6.4):

$$\frac{d\sigma^{\pi^+ \to E_{55}^{+++}}}{dx\,du} \Big/ \frac{d\sigma^{\pi^- \to p}}{dx\,du} = \frac{2}{15}\,\varphi(u) \qquad (6.5)$$

where $\varphi(u)$ is determined by the expression (5.3).

Unfortunately, no data are available in the reaction (6.3). There exist, however, experimental data on the π^- -meson inclusive production in pp - collisions:

$$p\,p \to \pi^- X \qquad (6.6)$$

This process is described by the diagram shown in Fig. 6.3.

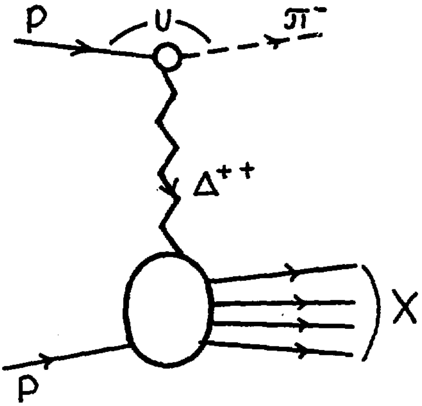


Fig. 6.3

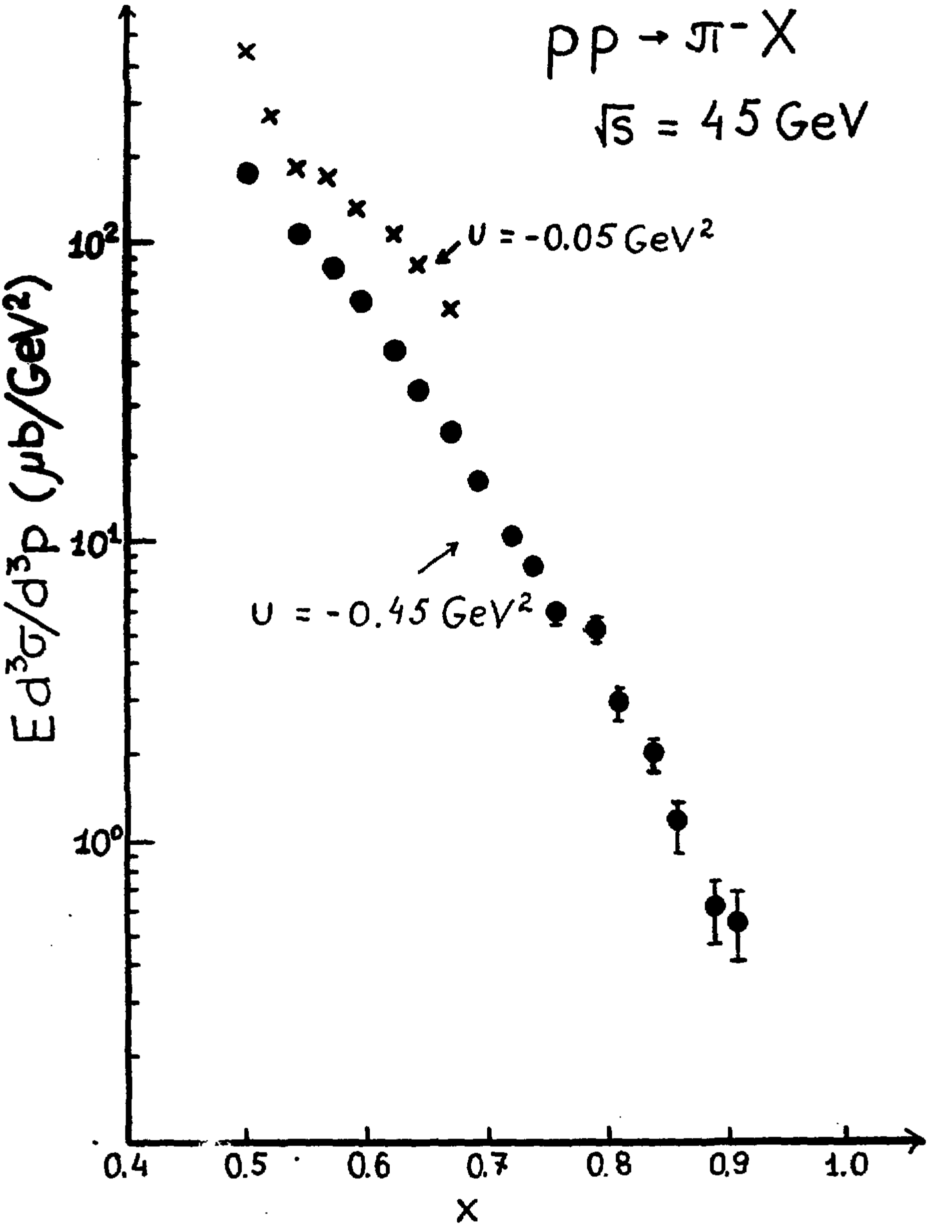
The cross section corresponding to this diagram has the form:

$$\frac{d\sigma^{p\to\pi^-}}{dx\,du} = (1-x)^{1-2\alpha_\Delta(u)} f_p(u)\, \sigma_{tot}^{\Delta_v p}(M_x^2, u) \qquad (6.7)$$

i.e. the ratio of the cross sections (6.4) and (6.7) is determined by $\sigma_{tot}^{\bar{\Delta}_v p}(M_x^2,u)/\sigma_{tot}^{\Delta_v p}(M_x^2,u) = \beta$. Take for β the value of the ratio $\sigma_{tot}^{\bar{p}p}(M_x^2)/\sigma_{tot}^{pp}(M_x^2)$. At $M_x^2 \gtrsim$ 5 GeV^2 the latter is $\gtrsim$ 1 , hence we may use formula (6.5) to estimate the ratio of the cross sections (6.2) and (6.7).

Fig. 6.4 shows the dependence of the π^- -meson distributions in pp-collisions at the transferred momentum squares U = -0.05 and U = -0.45 GeV^2 on the scaling variable X . The data are taken from [30] .

The experimental measurements of the π^- -meson spectra at larger X and smaller $|U|$ are absent. One may, however, expect (by analogy with the $X < 0.7$ region) that for $x > 0.7$ the cross section at $U \approx 0$ is approximately three times the one at $U = -0.45$.



rig. 6.4

Let us dwell now on the background contributions problem . In the case of the inclusive reactions the analysis of these contributions is rather intricate, since particles entering into the missing mass are not identified.

This complicates the concrete definition of the background subprocesses.

Nevertheless, using the analysis carried out in Sects 4 and 5 one can determine the kinematical restrictions which allow one to reduce the contribution of the background subprocesses to the $p\pi^+\pi^+$ $(\Delta^{++}\pi^+)$ – system. Consider, e.g. the diagram shown in Fig. 6.5:

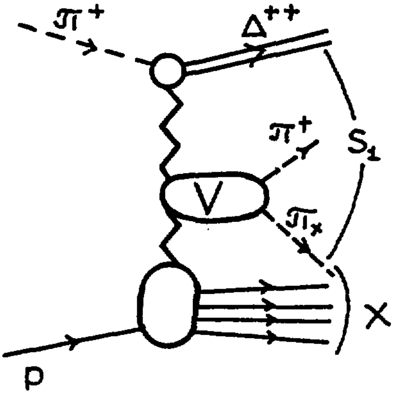


Fig. 6.5

This diagram is an inclusive analog of the background diagrams (4.2) and (5.2a).

From the analysis of Sect. 4 we know that to reduce the contribution of the diagram 6.5 to the $\Delta^{++}\pi^+$– system one should increase the relative momentum between the system $\Delta^{++}\pi^+$ and π_x (increase S_1). In the case of inclusive processes the condition of the large relative momentum between $\Delta^{++}\pi^+$ and π_x is formulated as a requirement for the system $\Delta^{++}\pi^+$ to carry the large momentum fractions,

$$1 - x_{\Delta^{++}\pi^+} \ll 1 \tag{6.8}$$

This requirement implies that the momentum fraction carried by the X-system is much less than that carried by the $\Delta^{++}\pi^+$– system (the lab. frame is considered). It is obvious that in this case $x_{\Delta^{++}\pi^+}$ is much larger than the momentum fraction of any particle a_{ix} entering into the missing mass:

$$x_{\Delta^{++}\pi^+} \gg x_{a_{ix}} \tag{6.9}$$

Consider now at greater length the $p\pi^+\pi^+$ – system which is produced from the fast-flying E^{+++} – resonance along the $E^{+++} \to \Delta^{++}\pi_E^+ \to p\pi_\Delta^+\pi_E^+$ scheme. In this case, for the p_Δ, p_p and $p_{\pi_i^+}$ momenta the following restrictions hold:

$$\frac{p_E}{M_E}(E_\Delta^* - p_\Delta^*) < p_\Delta < \frac{p_E}{M_E}(E_\Delta^* + p_\Delta^*)$$

$$\frac{p_E}{M_E}(E_{\pi_E^+}^* - p_\Delta^*) < p_{\pi_E^+} < \frac{p_E}{M_E}(E_{\pi_E^+}^* - p_\Delta^*) \tag{6.10}$$

$$\frac{p_\Delta}{M_\Delta}(E_p^* - p_p^*) < p_p < \frac{p_\Delta}{M_\Delta}(E_p^* + p_p^*)$$

$$\frac{p_\Delta}{M_\Delta}(E_{\pi_\Delta^+}^* - p_p^*) < p_{\pi_p^+} < \frac{p_\Delta}{M_\Delta}(E_{\pi_\Delta^+}^* + p_p^*) \tag{6.11}$$

In formulae (6.10) and (6.11) p_Δ^* and p_p^* are the decay momenta of $E \to \Delta\pi$ and $\Delta \to N\pi$ in the E and Δ c.m.s., respectively; E_i^* are the corresponding energies.

At M_E = 1.42 and M_Δ = 1.23 GeV we have:

$$0.79\,p_E < p_\Delta < 0.96\,p_E$$

$$0.04\,p_E < p_{\pi_E^+} < 0.21\,p_E \tag{6.12}$$

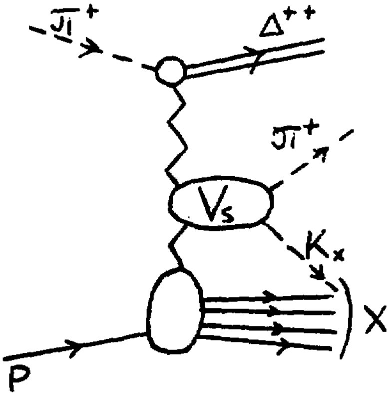
$$0.60\,p_\Delta < p_p < 0.97\,p_\Delta$$

$$0.03\,p_\Delta < p_{\pi_\Delta^+} < 0.40\,p_\Delta \tag{6.13}$$

One can see from these formulae that the allowed values of the π_i^+ -mesons momenta lie in a pretty wide range and even at very large $x_{p\pi^+\pi^+}$ the invariant mass $M_{\pi_i^+\pi_x}$ of the system $\pi_i^+\pi_x$ may be small and located in the resonance region of $\pi_i^+\pi_x$ – scattering. Therefore, under the investigation of the $p\pi^+\pi^+$ – system, besides the restrictions (6.9) on the total momentum of the whole system, additional restrictions on momenta of the π_i^+ -mesons themselves should be imposed.

The above analysis is general enough and holds also for the other background subprocesses, e.g. for the one shown in Fig. 6.6:

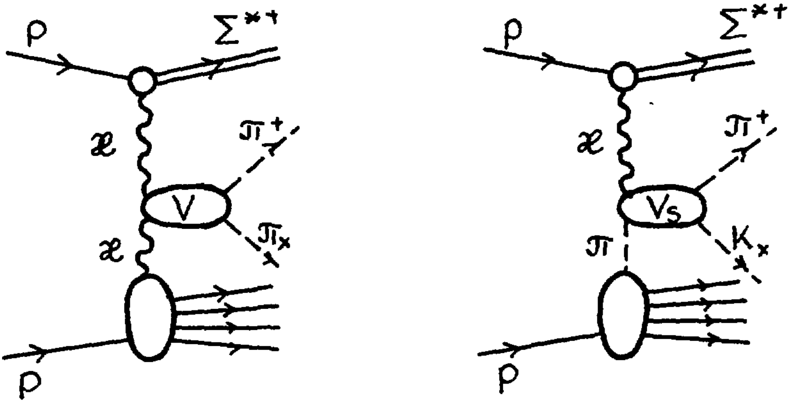
Fig. 6.6



Thus, to search effectively for the resonances in the $p\pi^+\pi^+(\Delta^{++}\pi^+)$-system produced in the π^+ -beam fragmentation region one should work at large $x_{p\pi^+\pi^+}$. Varying $x_{p\pi^+\pi^+}$ and the momentum fraction $x_{\pi_i^+}$ of π_i^+ -mesons from the $p\pi^+\pi^+$ -system at fixed $x_{p\pi^+\pi^+}$ we thus vary the relative energy between the $p\pi^+\pi^+$ -system and any particle a_{ix} entering into the missing mass and vary the mass $M_{\pi_i^+ a_{jx}}$. This makes it possible both to vary the background processes contribution and ascertain the nature of possible peaks in the system $p\pi^+\pi^+(\Delta^{++}\pi^+)$, for if those peaks have a kinematical origin, then their position and shape should vary under the above-mentioned variations of the kinematical configurations

7. Observation of the Exotic Hyperons.

Now discuss the choice of optimum reactions and measurement regimes to search for the S_E^*- and S_E -resonances. Just like in the case of nonstrange exotic baryons, the search for S_E^* and S_E seems to be more effective in the boson beam experiments. So, the background subprocesses shown in Fig. 7.1 contribute to the $\Lambda\pi^+\pi^+(\Sigma^{*+}(1385)\pi^+)$ - system produced in the incident proton fragmentation region.



a) b)

Fig. 7.1

These processes proceed via the strange boson trajectory exchange ($\varkappa = K, K^*, K^{**}, \ldots$), while the S_E^*-production is determined by the contribution of the exotic t-channel singularity with strangeness $S = -1$ and positive charge +1 (see Fig. 7.2):

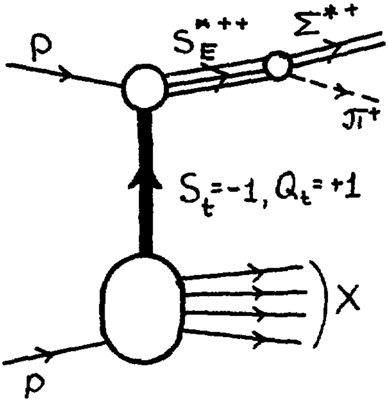
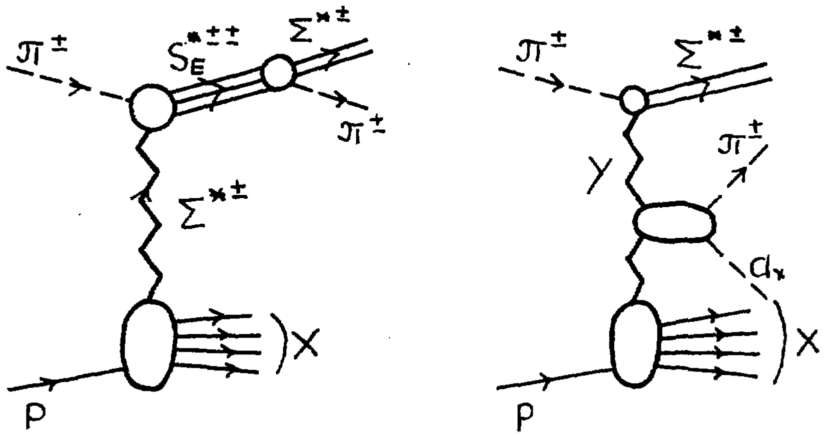


Fig. 7.2

In case of production in the boson (π^-, K^-) beam fragmentation region, the production mechanisms for the background system and the resonance are the same (both processes proceed via the baryon poles exchange), so the role of the kinematical reflections is not as dominant as for the production on p beams. Fig. 7.3 presents the diagrams describing the $\Sigma^{*\pm}\pi^{\pm}$-system production in the resonance (from S_E^*) and background processes.



a) b)

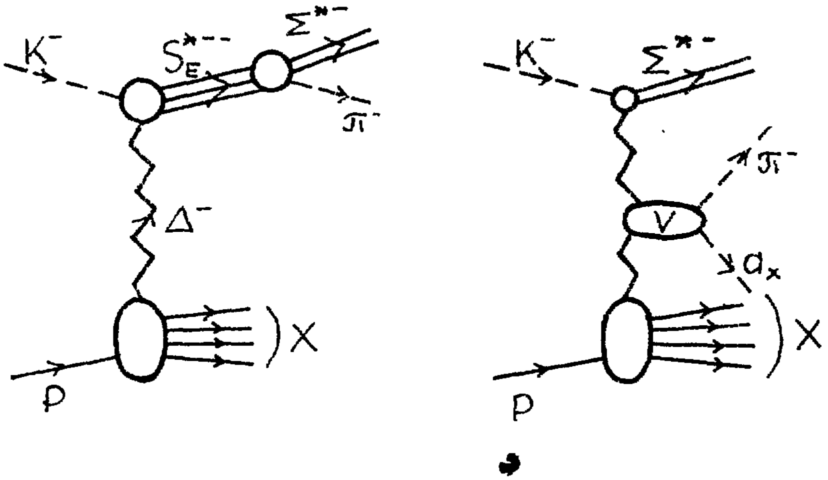
Fig. 7.3

Y denotes the Σ^*- and Σ- trajectories.

More effective seems the search for S_E^* (S_E) in the K^--beams experiments, since in this case $S_E^*(S_E)$ is produced due to the $\Delta(N,\Delta)$-trajectory exchange, the latter being in the j-plane on the right of the $\Sigma^*(\Sigma^*, \Sigma)$- trajectory. The diagrams for the main and background processes in case of S_E^*- production are plotted in Fig. 7.4 *).

---

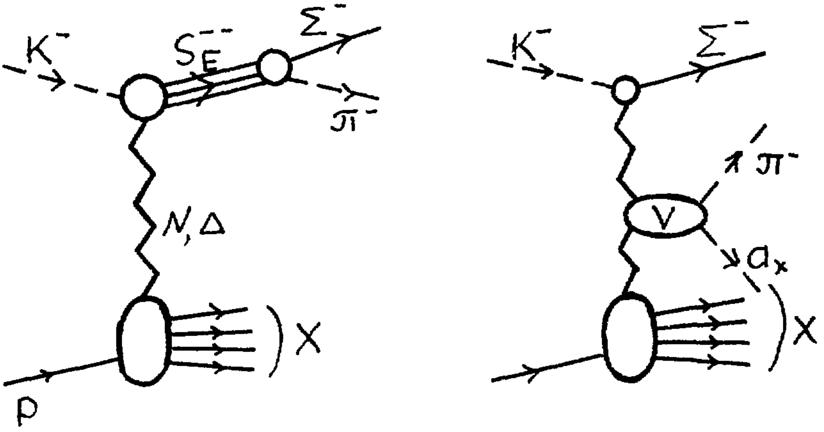
*) Note that the production of S_E^{*++} and S_E^{++} on the K^+-beams is determined by the contribution of the t-channel exotic baryon singularity with strangeness S = -2 and charge +1, and its cross section must be suppressed against the S_E^{*--} and S_E^{--} production cross section in the K^--beam experiments.



a) b)

Fig. 7.4

The analogous diagrams describing the S_E-production are shown in Fig. 7.5.



a) b)

Fig. 7.5

As to the choice of the kinematical region where the influence of the background processes is small, it is evident that the conclusions of Sects 4-6 are quite applicable to the analysis of the resonances in the $\Lambda\pi\pi$ - and $\Sigma\pi$ - systems.

In conclusion, let us dwell briefly on the search for the baryon resonances with S = -2, -3.

More preferable is the search for these resonances in the K^--beam experiments in the following systems: a) $\Xi^-\pi^-$; b) $\Xi^0\pi^-\pi^-$ and $\Xi^-\pi^0\pi_0$ with the selection $\Xi^{*-}(1520)\pi^-$;
c) $\Omega^-\pi_i$ ($\pi_i = \pi^-, \pi^0, \pi^+$).

8. Angular Distribution. The Resonance Spin and Parity.

To determine spins and parities of the resonances, the analysis of angular distributions of their decay products is necessary. We consider here the angular correlation between a- and b- particles in the rest frame of resonance d which decays as $d \to b+\pi \to a+\pi+\pi$ (see Fig. 8.1). Important is the fact that this correlation does not depend on the resonance d production dynamics and is determined only by the particle b alignment which depends on the resonance d spin-parity.

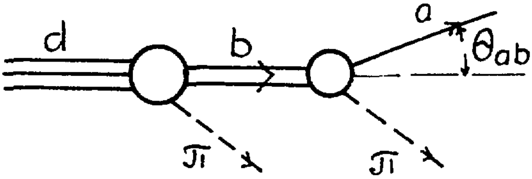


Fig. 8.1

Fig. 8.2 presents the calculations of $W(\theta_{ab})$-distributions as functions of $\cos\theta_{ab}$ at various $\mathcal{J}_d$ and P_d in case when $\mathcal{J}_b^{P_b} = 3/2^+$ (Δ-, Σ^*-resonances) and $\mathcal{J}_a^{P_a} = 1/2^+$ (nucleon, Λ-hyperon). The curves correspond to the masses M_d = 1.42, M_b = 1.23, M_a = 0.94.

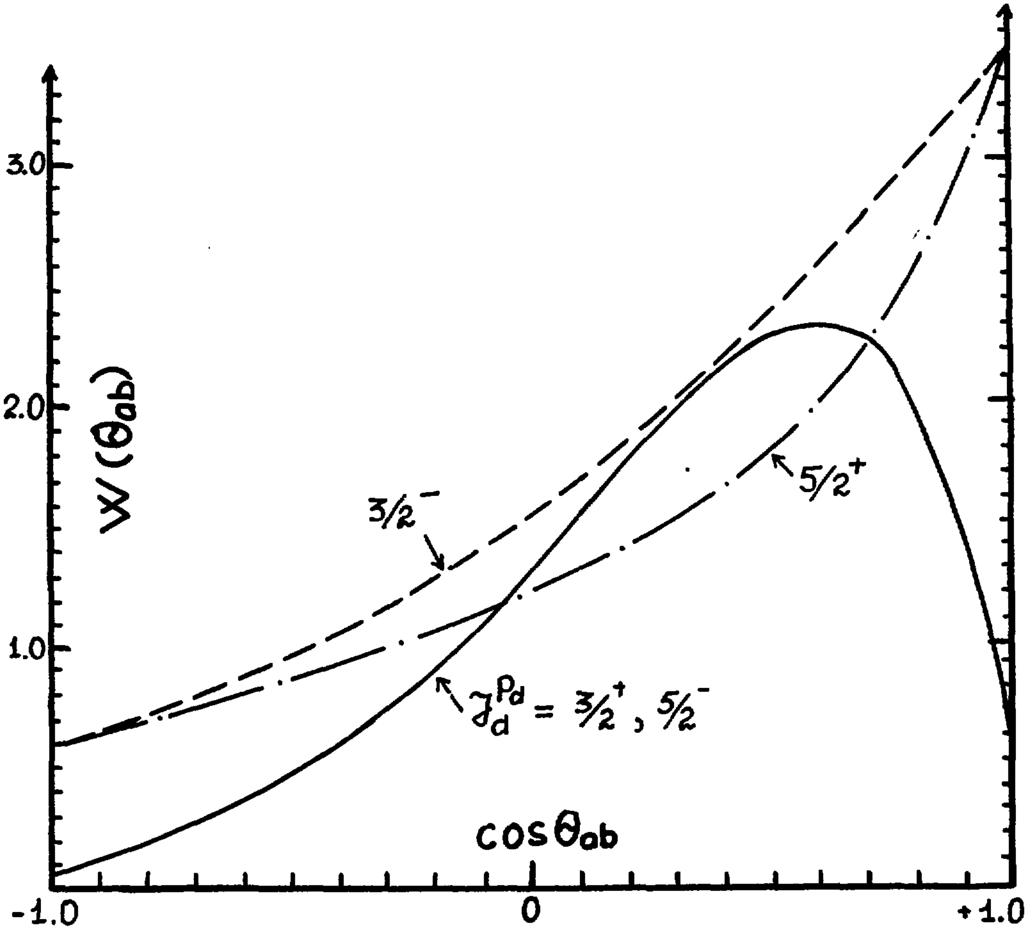


Fig. 8.2

9. Observation of Exotic Baryon Regge Trajectories.

There exits a highly attractive possibility to study the Regge trajectories, corresponding to the exotic baryons, in the reactions with the ordinary particle production.

Consider the inclusive process

$$\pi^- p \to \Delta^{++} X \tag{9.1}$$

The diagram describing the spectrum of Δ^{++} -resonances produced in the π^- -meson fragmentation region (the fast Δ^{++}) has at small transferred momenta ($|u| \lesssim 1$ GeV^2) the usual Regge form:

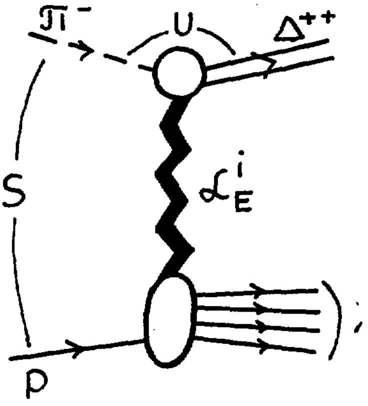


Fig. 9.1

where α_E^i are I = 5/2 baryon trajectories contributing to this process.

The cross section of process (9.1) is expressed through the contribution of the three-reggeon vertices (see Fig. 9.2) in the following way:

$$\frac{d\sigma^{\pi^-\to\Delta^{++}}}{dx\,du} = \sum_{\substack{i,j,\\R}} f_{ijR}(u)\left(\frac{s}{s_0}\right)^{\alpha_R(0)-1}(1-x)^{\alpha_R(0)-\alpha_i(u)-\alpha_j(u)} \qquad (9.2)$$

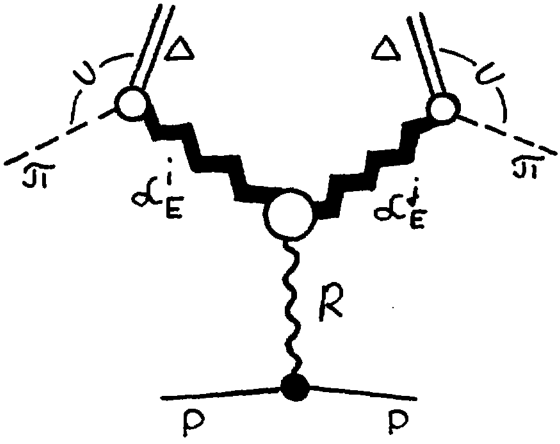


Fig. 9.2

where R are the boson Regge-trajectories $P, \rho, A_2, \omega, \dots$ (the pion pole does not contribute, since its residue in the lower vertex is equal to zero). As usual, approximate the expression (9.2) by the sum of two terms:

$$\frac{d\sigma^{\pi^-\to\Delta^{++}}}{dx\,du} = f_P(u)(1-x)^{1-2\alpha_E^{eff}(u)} + \frac{1}{\sqrt{s}}\, f_R(u)(1-x)^{0.5-2\alpha_E^{eff}(u)} \qquad (9.3)$$

The first term in (9.3) corresponds to the contribution of the vacuum trajectory, while the second one to the effective contribution of the secondary trajectories R with $\alpha_R(0) \approx 0.5$. $\alpha_E^{eff}(u)$ is the effective exotic baryon trajectory.

It is seen from (9.3) that varying x, u and s one can determine $\alpha_E^{eff}(u)$ as well as $f_P(u)$ and $f_R(u)$. In the same way one can investigate the exotic baryon trajectories with S = -1 and I = 2, analysing the inclusive spectra of $\Sigma^{*\pm}(1385)$ and $\Sigma^{\pm}$ hyperons in the fragmentation region of $\pi^{\mp}$-beams (see Fig. 9.3).

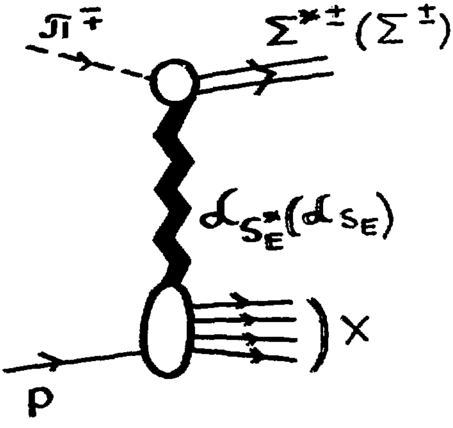


Fig. 9.3

10. The Experimental Feasibilities to Search for the Exotic Resonances with the OMEGA Spectrometer.

In the previous sections we have analysed the processes and kinematical configurations which are most reasonable for studying the exotic baryon resonances. In this section we show that the OMEGA parameters (energy range, luminosity, capability of the particles identification in the wide momentum range and the mass resolution) allow one to search for these resonances and investigate them at a high confidence level. The analysis was performed for E_{55}^{+++}- baryon production in $\pi^+ p$ -collisions at the π^+ -beam energy range from 30 to 200 GeV/c.

a) Kinematics, registration and identification of particles.

E^{+++} identification has to be done by the analysis of the effective mass distribution of the fast-flying system $p\pi^+\pi^+$ (the mass ranges from the threshold up to 1.8 GeV) with the extraction of Δ_{33} -resonance region in the $p\pi^+$- system. The measurement of the π^+ -mesons momenta in the range 0.5 ÷ 60 GeV/c and the protons ones in the range 5 ÷ 200 GeV/c is necessary (see Sect. 6). The square of momentum transfer from the beam to the $p\pi^+\pi^+$- system is in the range from U_{max} to -1 $(GeV/c)^2$ (the $p\pi^+\pi^+$- system transverse momenta are 0 ÷ 1 GeV/c). This kinematical domain is completely covered by the OMEGA acceptance. The particles with 0.5 ÷ 5 GeV/c momenta are detected with the forward detectors. The 5÷80 GeV/c particles are registered and identified by means of the forward detectors. drift chambers, threshold Č-counters and ring-image Č-counters. For the particle identification in the region above 80 GeV/c the XTP-detector is used. In the momenta region, where it is difficult to separate p and K^+, the restriction on the invariant mass of π^+ -meson and proton in the Δ_{33}-isobar mass region is to allow one to reduce essentially the $\pi^+\pi^+K^+$- configuration background.

b) The system $p\pi^+\pi^+(\Delta^{++}\pi^+)$ effective mass resolution of the OMEGA spectrometer.

As shown in Sect. 2, the expected width of low-lying exotic resonances may be relatively small ($\Gamma_E \approx 10$ MeV); therefore the set-up mass resolution is essential to identify them reliably in the presence of non-resonance background.

For precise calculations, the correct simulations of the studied process which take into account the real parameters of OMEGA and the track identification program (TRIDENT) are needed.

The estimations of the OMEGA mass resolution (in the approximation of the momentum and angular "ideal" resolutions) give the value 3÷10 MeV for the resonance masses 1.4 ÷ 2.0 GeV.

c) Estimation of number of E_{55}^{+++} production events for the OMEGA.

The expected number of events for E_{55}^{+++} production was estimated using the formula:

$$\mathcal{N}_{E_{55}} = \sigma_{E_{55}} \cdot \mathcal{N}_H \cdot I \cdot t$$

where $\sigma_{E_{55}}$ is E_{55}^{+++} production cross section

$\mathcal{N}_H$ is the number of the hydrogen target atoms per cm^2 ($N_H \approx 2.5 \cdot 10^{24}/\mathrm{cm}^2$)

I is the average intensity of π^+-mesons beam ($I \approx 5 \cdot 10^5$/sec)

t is the exposure time ($\approx$ 480 hours).

Taking into account the theoretical estimations of the cross sections (see (5.2) and (6.5)) and the experimental U -dependence [29,30] , we obtain for the reaction

$$\mathcal{N}_{E_{55}} = 20.000\,, \qquad p_{lab}^{\pi^+} = 30\ \mathrm{GeV/c}$$

$$\mathcal{N}_{E_{55}} = 2.000\,, \qquad p_{lab}^{\pi^+} = 90\ \mathrm{GeV/c}$$

In the inclusive production case, $\sigma_{E_{55}}$ is energy-independent (has a scaling nature).

The estimations show that for

$$\sigma_{E_{55}} = \int_{0.9}^{1} dx \int_{-1}^{U_{max}} du \, \frac{d\sigma^{\pi^+ \to E_{55}^{+++}}}{dx\, du}$$

$$\mathcal{N}_{E_{55}} \approx 30.000$$

The obtained estimations show that the OMEGA spectrometer at CERN is suitable to realize (without any modification) the search for the exotic resonances and their investigation at a high experimental level.

The authors are grateful to A.Ts. Amatuni for his permanent interest in the work and useful discussions.

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