FORMATION OF THE \(N^*(3,3)\) ISOBAR IN THE REACTION \(\pi^-p \to \pi^+\pi^-n\)

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FORMATION OF THE $N^*(3,3)$ ISOBAR IN THE REACTION $\pi^- p \to \pi^+\pi^- n$

The reaction under study is especially convenient for analyzing the $N^*(3,3)$ isobar, since the probability of producing a "pure" $(3,3)$ $(\pi^- n)$ state is an order of magnitude higher than that of the $(\pi^+ n)$ state, because in the energy region studied the reaction proceeds mainly from the initial state with isotopic spin $T = 1/2$ ([1]).

The amplitude for formation of the N^* isobar is the most important characteristic, necessary both for carrying out a partial-wave analysis of the reaction considered and for comparison with predictions of theories based on various symmetry groups.

Table 1

E_0, MeV	a	b	φ	χ^2/χ^2_{exp}	a	χ^2/χ^2_{exp}	b	χ^2/χ^2_{exp}
	Tabulated parameters of the isobar $M = 1238$, $\Gamma = 120$				**Background only**		**Isobar only**	
365	0.87 ± 0.10	0.57 ± 0.20	1.94 ± 0.28	0.94	0.86 ± 0.03	1.6	0.71 ± 0.03	11.8
430	0.79 ± 0.22	1.26 ± 0.28	1.62 ± 0.54	1.2	1.19 ± 0.04	11.8	1.40 ± 0.04	3.2
476	1.28 ± 0.20	1.97 ± 0.27	1.06 ± 0.23	1.7	1.55 ± 0.05	15.1	1.77 ± 0.05	4.4
551	1.02 ± 0.34	2.47 ± 0.33	2.07 ± 0.31	4.3	1.61 ± 0.07	21.0	2.19 ± 0.07	3.4

E_0, MeV	a	b	φ	$\chi^2/\chi^2_{\text{exp}}$	a	$\chi^2/\chi^2_{\text{exp}}$	b	$\chi^2/\chi^2_{\text{exp}}$
604	1.23 ± 0.42	2.09 ± 0.48	1.76 ± 0.51	1.1	1.91 ± 0.07	11.1	2.19 ± 0.08	2.2
680	0.95 ± 0.72	2.29 ± 0.56	1.25 ± 1.29	0.57	2.19 ± 0.08	15.0	2.66 ± 0.08	1.4
780	1.96 ± 0.62	2.24 ± 0.77	1.51 ± 0.74	1.3	2.80 ± 0.08	9.0	2.90 ± 0.08	6.1

To determine the isobar amplitudes we analyzed the experimentally obtained distribution of values of the squares of the effective $(\pi^- n)$ masses, kindly provided to us by Dr. Kirsch ([2]). In order that the distribution over the squares of the effective $(\pi^- n)$ masses should not be distorted by interference effects of (πN) and $(\pi\pi)$ in the final state, we used the procedure for constructing conjugate points proposed in ([3]).

The differential cross section of the reaction $\pi^- p \to \pi^+\pi^- n$ can be represented in the form

$$\frac{d\sigma}{d\omega^2} = \Phi(\omega^2)\left\{a^2 k_a + b^2 k_b \frac{\pi^{-1}\Gamma\omega_*}{(\omega^2-\omega_*^2)^2 + (\Gamma\omega_*)^2} + \right.$$

$$\left. +2ab(k_a k_b)^{1/2}\cos\varphi\left[\frac{\pi^{-1}\Gamma\omega_*}{(\omega^2-\omega_*^2)^2+(\Gamma\omega_*)^2}\right]^{1/2}\right\}. \quad (1)$$

Here ω is the mass of the $(\pi^- n)$ system and ω_* is the fixed mass of the isobar; a and b are the amplitudes of the background and the isobar, respectively; φ is the phase shift; $\Phi(\omega^2)$ is a function representing the phase volume; k_a and k_b are normalization factors. The form of the dependence of the isobar width on mass is taken from the theory of nuclear reactions.

By the method of minimizing the functional, three parameters of formula (1), a, b, and φ, were found that satisfy the experimental data for

of pion energies for values of χ^2 that do not differ greatly from the expected ones. The values of these parameters and $\chi^2/\chi^2_{\text{exp}}$ are presented in Table 1. A description of the mass distribution $d\sigma/d\omega^2$ by means of only one background or only one isobar amplitude proved impossible (see Table 1). At an energy of 365 MeV, $d\sigma/d\omega^2$ is well described only by the background amplitude. In the case where the interference ($\varphi = 1.57$ radians) between the isobar and the background is neglected, the values of the amplitudes and the ratio $\chi^2/\chi^2_{\text{exp}}$ agree, within the errors, with the values indicated in columns 1-4. Therefore, on the basis of the materials available to us, no reliable estimates can be made of the contribution of interference between the isobar and the background.

Fig. 1

Figure 1: Fig. 1

Taking into account the results presented in Table 1 and the relation between the cross sections of N^{*-} and N^{*+}, calculated from isospin relations, one can determine the values of the total isobar cross section. These values are shown in Fig. 1 together with the values obtained on the basis of the Olsson–Yodh model ([1]) and with the contribution of various partial waves to the inelastic cross section, obtained from the results of a phase-shift analysis ([4]). From a comparison of these data it is seen that up to an energy of 400 MeV the inelastic cross section in the D_{13} state is smaller than the isobar-production cross section. It follows from this that for $E \leq 400$ MeV the isobar is produced predominantly in the p-state (the P_{11} wave). Olsson and Yodh in their model hypothetically assume production of the isobar in an s-state from the D_{13} state. Therefore their estimates of the isobar-production cross section for the energy range 350-450 MeV must be treated with caution. At higher energies our results and theirs agree.

Fig. 1. Dependence of the production cross section of the (3/3) isobar on energy.
a—data of this work; *b*—Olsson–Yodh data; *v*—inelastic cross section in the P_{11} state; *g*—inelastic cross section in the D_{13} state.

The states of isobar production are characterized by the angular distribution of π^+-mesons in the c.m.s., which are recoil pions from the formed $(\pi^- n)$-isobar. Usually only events lying in the region of the isobar band $M_{\pi^- n} = (1238 \pm 60)$ MeV are taken into account. It should be noted, however, that in the isobar band there is an admixture of "background" events, just as outside it there are isobar events. In order to obtain the "true" angular distribution, one can use the previously determined isobar cross sections and represent the angular distributions of π^+-mesons in two regions differing in the mass $M_{\pi^- n}$ in the form:

$$\frac{dN}{d(\cos\theta)} = \sigma^i_{\text{iz}} \sum_{l=0}^{n} A_l P_l(\cos\theta) + \sigma^i_{\phi} \sum_{l=0}^{n} A'_l P_l(\cos\theta). \tag{2}$$

Here σ^i_{iz} and σ^i_{ϕ} are the cross sections of the isobar and the background in the i-th region; A_l and A'_l are coefficients determining the true angular distribution of the isobar and of the background; P_l are Legendre polynomials. Considering in this form the angular distributions of π^+-mesons simultaneously in the two regions, by the minimization method we obtained the coefficients A_l and A'_l (Table 2 gives the coefficients A_l, since we are interested only in the angular distribution of the isobar), up to and including A_2 and A'_2, since already these coefficients up to an energy of 550 MeV were practically equal to zero. The coefficients found remain constant within the errors when the width of the isobar region is varied; consequently, it may be assumed that the coefficients in Table 2 do indeed reflect the angular distribution of the isobar. As follows from the table, the angular distribution is anisotropic, and the degree of anisotropy decreases with increasing energy of the π^--mesons.

Representing the reaction under consideration in the form $\pi^- p \to \pi^+ N^*$, one can write for the angular distribution of the π^+ mesons

$$\frac{dN}{d(\cos\theta)} \sim \sum_{\alpha,\beta,l} A_l^{\alpha\beta} P_l(\cos\theta),$$

where $A_l^{\alpha\beta}$ are coefficients that determine the contribution of the various partial waves to the angular distribution; α and β are indices associated with the quantum numbers of the selected partial amplitudes in the final state. Comparison of $A_l^{\alpha\beta}$ with the obtained A_l makes it possible to establish the presence of different partial waves and interferences between them.

Table 2

Coefficients	Energy, MeV	Energy, MeV	Energy, MeV	Energy, MeV
	365	430	476	551
A_0	26.9 ± 9.4	12.7 ± 1.9	7.9 ± 1.0	3.3 ± 0.6
A_1	46.0 ± 15.7	15.9 ± 3.4	4.4 ± 1.6	1.6 ± 1.0
A_2	5.4 ± 20.6	0.9 ± 4.3	0.6 ± 2.1	-1.7 ± 1.3

In the phase-shift analysis of Lovelace et al. ([4]), the contribution to the inelastic cross section in the energy region considered is given by the states P_{11} and D_{13}, which corresponds to p-, s-, and d-formation of the isobar $PP1$, $DS3$, $DD3$ (notation: orbital angular momentum of the initial state, orbital angular momentum of the recoil pion, doubled total angular momentum of the initial state). Each of these three states taken separately gives a contribution to the differential cross section that does not depend on angle; i.e., the anisotropy of the angular distribution can be explained only by interference. It is therefore clear that at least two states must be present in the partial-wave analysis. Of the states indicated, the combinations $PP1DS3$ and $PP1DD3$ contribute to the coefficients at $P_1(\cos\theta)$, with a positive value of the coefficient given only by $PP1DD3$. The negative coefficient at $P_2(\cos\theta)$ appearing at an energy of 550 MeV corresponds to the interference $DS3DD3$. Consequently, on the basis of this phase-shift analysis, the angular distribution of the π^+ mesons is explained by the presence of all three waves corresponding to s-, p-, and d-formation of the isobar; incidentally, the s-formation of the isobar up to an energy of 450–500 MeV is clearly small.

In the phase-shift analysis of Bareyre ([5]), the contribution to the inelastic cross section is given, in addition to the waves listed above, by the wave P_{13}, which corresponds to the final state $PP3$. The interference $PP3DS3$ gives a positive coefficient at $P_1(\cos\theta)$, and it seems possible to describe the angular distribution by states corresponding only to S- and P-production of the isobar. However, the interference $PP1PP3$ and $PP3PP3$ leads to negative coefficients at $P_2(\cos\theta)$, which does not satisfy the experimental data at energies below 500 MeV. It is evident that further progress in the partial-wave analysis of inelastic processes depends to a considerable degree on the phase-shift analysis of elastic πN scattering.

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Note: Figure translations are in progress. See original paper for figures.