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DETERMINATION OF ELECTROMAGNETIC FORM FACTORS OF NUCLEON RESONANCES FROM DATA ON $\gamma p \to \Delta^{++}\pi^-$ AND $\gamma p \to p\rho^0$ REACTION CROSS SECTIONS

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A method for extracting form factors N^* from the experimental data on cross sections of exclusive reactions $\gamma_{r,v}p \to \Delta^{++}\pi^-$ and $\gamma_{r,v}p \to p\rho^0$ has been developed. It is shown that the method ensures stable calculation of form factors with an inaccuracy of about 10% if the errors in measuring cross sections of said quasi-two-particle reactions do not exceed 1%.

INTRODUCTION

At present a great interest is being shown in studying properties of baryon resonances. In many respects this is caused by commissioning for service a large international center TJNAF in the USA [1, 2]. A combination of the 4π-detector CLAS with a luminosity of 10^{34} cm$^{-2}\cdot$s^{-1} and a continuous beam of electrons with energy up to 4 GeV offers new opportunities for studying nucleon resonances in exclusive production channels under the effect of real and virtual photons. Studying the exclusive channel with the formation of two pions acquires special importance. At $W > 1.7$ GeV the contribution of this channel becomes basic in the processes of interaction of real and virtual photons with the proton. The two-pionic mode of decay becomes dominant for N^* with masses greater than 1.5 GeV. Modern constituent quark models predict the existence of a large number of resonant states N^* with masses varying in the range from 1.8 to 2.5 GeV [3–5], not, however, detected experimentally — the so-called missing-resonances. According to models [3–5], the coupling between missing-resonances and decay channels that lead to the formation of two pions in the final state, is much greater than that with channels with the formation of one pion. Thus, the investigation of production processes for two pions on a proton opens up the appreciable opportunities for searching and investigating missing-resonances.

According to the systematics of the experimental data available on the processes of electro- and photoproduction of two pions on the proton [6, 7], the main mechanisms of the reaction $(e, e'p\pi\pi)$ are quasi-two-particle processes

$$\begin{aligned} \gamma_{r,v}p &\to \Delta^{++}\pi^- \to (p\pi^+)\pi^-, \\ \gamma_{r,v}p &\to \quad p\rho^0 \quad \to p(\pi^+\pi^-), \end{aligned} \tag{1}$$

where the subscripts r and v denote real and virtual photons. Accordingly there arises the necessity of developing methods for extracting electromagnetic form factors $A_{1/2}$, $A_{3/2}$, and$C_{1/2}$ of resonant states N^* from the experimental data on quasi-two-particle processes (1). The initial experimental data are the cross sections of processes with the formation of a $(p\pi^+\pi^-)$-system in the final state, from which the cross

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sections of quasi-two-particle reactions are determined (1). The methods for determining the cross sections of quasi-two-particle processes are the subject of an independent investigation beyond the scope of the present work.

A model that describes the differential cross sections of $\gamma_{r,v}p \to \Delta^{++}\pi^-$ and $\gamma_{r,v}p \to p\rho^0$ reactions was developed in [8]. This model was used as a basis for the method of determining electromagnetic form factors N^* from the data on the cross sections of quasi-two-particle reactions studied in the present paper.

DESCRIPTION OF THE METHOD

In the model described in [8] the differential cross sections are described by an ensemble of processes of excitation N^* in the entrance channel γp and their subsequent decay into the final states $\Delta^{++}\pi^-$ and $p\rho^0$, and also by nonresonance processes leading to the formation of $\Delta^{++}\pi^-$ and $p\rho^0$ systems in the final state. For the $\Delta^{++}\pi^-$-channel the nonresonance mechanisms are described by the collection of Born terms [9] for the effects of interaction in the initial and in the final state [10]. Nonresonance processes in the $p\rho$-channel are described in the approximation of meson diffraction scattering on the proton [11].

Electromagnetic form factors $A_{1/2}(Q^2)$, $A_{3/2}(Q^2)$, and $C_{1/2}(Q^2)$ of resonant states N^* are regarded as free parameters, and their values are determined in a fitting procedure from the condition of the best reproduction of experimental data on the cross sections of $\gamma_{r,v}p \to \Delta^{++}\pi^-$ and $\gamma_{r,v}p \to p\rho^0$ reactions. For carrying out the fitting procedure, a computer program was developed on the basis of the module MINUIT [12]. The fitting procedure employs a model described in [9], which relates the parameters being fitted, i.e., form factors $A_{1/2}$, $A_{3/2}$, and $C_{1/2}$, with the cross sections of the quasi-two-particle processes $\gamma_{r,v}p \to \Delta^{++}\pi^-$ and $\gamma_{r,v}p \to p\rho^0$ being measured.

Table 1

Parameters N^* used in calculating quasi-two-particle channels $\gamma p \to \Delta^{++}\pi^-$ and $\gamma p \to p\rho^0$ [13]

Resonance	$A_{1/2}$ ($\mathrm{GeV}^{-1/2}$)	$A_{3/2}$ ($\mathrm{GeV}^{-1/2}$)	$\Gamma_{\gamma p}(\Gamma_x/\Gamma_{tot})$ (keV)
Channel $\gamma p \to \Delta^{++}\pi^-$; $\Gamma_x = \Gamma_{\Delta\pi}$			
$P_{11}(1440)$	−0.072		35
$D_{13}(1520)$	−0.022	0.163	12
$S_{11}(1650)$	0.052		7
$D_{15}(1675)$	0.018	0.018	8
$F_{15}(1680)$	−0.014	0.136	33
$S_{31}(1620)$	0.030		14
$D_{33}(1700)$	0.114	0.091	300
$F_{35}(1905)$	0.037	−0.031	14
$F_{37}(1950)$	−0.085	−0.101	75
Channel $\gamma p \to p\rho^0$; $\Gamma_x = \Gamma_{p\rho}$			
$F_{15}(1680)$	−0.014	0.136	33
$P_{13}(1720)$	0.027	−0.026	60
$D_{33}(1700)$	0.114	0.091	280
$F_{35}(1905)$	0.037	−0.031	50
$F_{37}(1950)$	−0.085	−0.101	15

Table 2

Results of calculating form factors $A_{1/2}$ and $A_{3/2}$ from data on differential cross sections for $\gamma p \to \Delta^{++}\pi^-$ and $\gamma p \to p\rho^0$ channels with different values of variance σ (A_{in} is the initial and A_{calc} is the calculated value of the form factor)

Resonance, helical amplitude	$\frac{\lvert A_{\text{in}} - A_{\text{calc}}\rvert}{A_{\text{in}}}$ (%) at $\sigma = 0.5\%$	$\frac{\lvert A_{\text{in}} - A_{\text{calc}}\rvert}{A_{\text{in}}}$ (%) at $\sigma = 5\%$	$\Gamma_{\gamma p}(\Gamma_x/\Gamma_{\text{tot}})$ (keV)
Channel $\gamma p \to \Delta^{++}\pi^-$; $\Gamma_x = \Gamma_{\Delta\pi}$			
$P_{11}(1440)$, $A_{1/2}$	2.5	49	35
$D_{13}(1520)$, $A_{1/2}$	15	73	4.8
$D_{13}(1520)$, $A_{3/2}$	0	2	120
$S_{11}(1650)$, $A_{1/2}$	24	340	7
$D_{15}(1675)$, $A_{1/2}$	26	26	5.3
$D_{15}(1675)$, $A_{3/2}$	1	150	5.3
$F_{15}(1680)$, $A_{1/2}$	2	100	1.3
$F_{15}(1680)$, $A_{3/2}$	3	0.5	33
$S_{31}(1620)$, $A_{1/2}$	20	84	14
$D_{33}(1700)$, $A_{1/2}$	0.1	14	180
$D_{33}(1700)$, $A_{3/2}$	2	21	105
$F_{35}(1905)$, $A_{1/2}$	21	0.3	14
$F_{35}(1905)$, $A_{3/2}$	6	73	14
$F_{37}(1950)$, $A_{1/2}$	5	43	30
$F_{37}(1950)$, $A_{3/2}$	0.1	5	45
Channel $\gamma p \to p\rho^0$; $\Gamma_x = \Gamma_{p\rho}$			
$F_{15}(1680)$, $A_{1/2}$	4	250	1.3
$F_{15}(1680)$, $A_{3/2}$	0.3	2	33
$P_{13}(1720)$, $A_{1/2}$	0	2	48
$P_{13}(1720)$, $A_{3/2}$	3	20	16
$D_{33}(1700)$, $A_{1/2}$	0.2	0.4	168
$D_{33}(1700)$, $A_{3/2}$	0.9	6	100
$F_{35}(1905)$, $A_{1/2}$	1	10	50
$F_{35}(1905)$, $A_{3/2}$	0.6	7	50
$F_{37}(1950)$, $A_{1/2}$	0.1	0.4	6
$F_{37}(1950)$, $A_{3/2}$	0.3	4	9

The quantity $\Gamma_{\gamma p}$ is taken here for the state N^* with corresponding helicity.

FITTING PROCEDURE AND RESULTS

At present the accuracy of experimental data on the cross sections of the $\gamma_{r,v}p \to \Delta^{++}\pi^-$ and $\gamma_{r,v}p \to p\rho^0$ reactions does not allow us to carry out the unambiguous determination of the form factors N^* contributing to this process. Therefore, we have calculated, within the framework of the model [8], the differential cross sections $d\sigma(W,\theta)/d\Omega$ of the $\gamma_{r,v}p \to \Delta^{++}\pi^-$ and $\gamma_{r,v}p \to p\rho^0$ reactions, where W is the energy of colliding particles, θ is the angle of emission of the π^- or ρ^0-meson in the CMS. The N^* involved in the calculations, and the values of helical amplitudes $A_{1/2}$ and $A_{3/2}$ at the photon point are presented in Table 1. The relative contribution of resonances to the reaction cross section is determined by the values of $\Gamma_{\gamma p}(\Gamma_{\Delta p}/\Gamma_{\text{tot}})$ and $\Gamma_{\gamma p}(\Gamma_{p\rho}/\Gamma_{\text{tot}})$, where $\Gamma_{\gamma p}$, $\Gamma_{\Delta p}$ and $\Gamma_{p\rho}$ are the partial decay widths of the resonant states N^* in the channels γp, $\Delta^{++}\pi^-$, and $p\rho^0$, and Γ_{tot} is the total width. The N^* involved in the calculations cover all the resonances with the status $* * **$ [13], for which reliable information on the above-said partial widths is available and which make an appreciable contribution to the corresponding channel, i. e., with $\Gamma_{\gamma p}(\Gamma_{\Delta p}/\Gamma_{\text{tot}}) > 5$ keV and $\Gamma_{p\rho}(\Gamma_{\Delta p}/\Gamma_{\text{tot}}) > 10$ keV. The cross sections thus calculated were regarded as quasi-data, from which the values of the form factors were calculated with the help of the fitting procedure.

The extraction of form factors was carried out both from the quasi-data not subjected to statistical disturbance, and from the quasi-data normally distributed near the calculated value of the cross section with variance $\sigma = 0.5\%$ and 5%. As the initial values of the form factors $A_{1/2}$ and $A_{3/2}$ being calculated, the values lying within 30% of the "true" ones presented in Table 1 were taken.

When the form factors are calculated from the undisturbed quasi-data, the obtained values exactly coincide with the initial ones. This testifies to the stability of the form factors N^* calculating procedure. The accuracy of calculating the form factors in the presence of statistical disturbances from the quasi-data is characterized by relative errors in the calculated values of form factors (Table 2). As it follows from the data presented in Table 2, when the cross section values fluctuate with $\sigma = 0.5\%$, the form factors are calculated with good accuracy (error $\pm 10\%$). For resonances making a greater contribution to the process cross section (greater value of $\Gamma_{\gamma p}(\Gamma_{\Delta p}/\Gamma_{\text{tot}})$ or $\Gamma_{\gamma p}(\Gamma_{p\rho}/\Gamma_{\text{tot}})$, the accuracy of the form factors proves to be higher. When the disturbance increases up to 5%, for the reaction $\gamma_r p \to \Delta^{++}\pi^-$ the accuracy of form factors reconstruction proves to be lower than that acceptable for the extraction of information on their structure. In the channel $\gamma_r p \to p\rho^0$ with the inaccuracy smaller than 10%, only the form factors of the most strongly excited resonances $D_{33}(1700)$ and $F_{35}(1905)$ are calculated. Therefore, for the determination of form factors N^* with an error not less than 10% the permissible errors in measuring the cross sections of quasi-two-particle channels should not exceed 1%.

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