Mechanism of Pion Production in αp Scattering at 1 GeV/nucleon

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The one-pion and two-pion production in the $p(\alpha, \alpha')X$ reaction at an energy of $E_\alpha = 4.2$ GeV has been studied by simultaneous registration of the scattered α' particle and the secondary proton or pion. The obtained results demonstrate that the inelastic α-particle scattering on the proton at the energy of the experiment proceeds either through excitation and decay of the Δ resonance in the projectile α particle, or through excitation in the target proton of the Roper resonance, which decays mainly on a nucleon and a pion or a nucleon and a σ meson – a system of two pions in the isospin $I = 0$, S-wave state.

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1 Introduction

A study of inelastic αp scattering at an energy of ~ 1 GeV/nucleon is of significant interest since it is related, in particular, to the problem of the $N(1440)P_{11}$ (Roper) resonance. The Roper resonance [1] is the lowest positive-parity excited state N^* of the nucleon, and in many respects it is a very intriguing and important resonance. Morsch *et al.* [2, 3] have interpreted the excitation of the Roper resonance in inelastic αp scattering as the breathing-mode ($L = 0$) monopole excitation of the nucleon. In this interpretation, the $N(1440)$ resonance mass is related to the compressibility of the nuclear matter (on the nucleonic level). This resonance also plays an important role in many intermediate-energy processes, in the three-body nuclear forces and in the swelling of nucleons in nuclei. The investigation of the $N(1440)$ resonance was the goal of numerous theoretical and experimental studies. This activity was motivated by the still not properly understood nature of the resonance, its relatively low mass and anomalously large width of a few hundred MeV.

The Roper resonance was observed and studied for the first time in the πp scattering partial-wave analyses [1, 4–7]. The fact that the Roper resonance is also strongly excited in αp scattering was quite puzzling. To understand the excitation of this resonance in different reactions, Morsch and Zupranski [3] performed a combined analysis of the data of πN-, αp- and γp-scattering experiments, with the conclusion that the $N(1440)$ state represents a structure formed of two resonances, one understood as the nucleon breathing mode and the other one as an excited state of the $\Delta_{3,3}(1232)$ (Δ) resonance. The first resonance is strongly excited by scalar probes, like in αp scattering, whereas the second one is excited in spin-isospin-flip reactions, like in πN scattering. The two-resonance picture of $N(1440)$ and the breathing-mode excitation of the proton was also discussed by the same authors [8] in a reanalysis of high-energy pp- and πp-scattering data.

An advantage of studying the Roper resonance in an αp-scattering experiment, as compared to πN, NN and γN experiments, is that in the case of αp scattering the number of the reaction channels is rather limited. At an energy of ~ 1 GeV/nucleon, the Roper resonance is strongly excited in αp scattering, whereas the contribution from excitation of other baryon resonances is expected to be small [9].

Inelastic αp scattering was investigated previously at $E_\alpha = 4.2$ GeV in an inclusive experiment [2] at the Saturne-II accelerator in Saclay using the SPES4 magnetic spectrometer. The energy distribution of the scattered α particles from the $p(\alpha, \alpha')X$ reaction was studied, and a strong excitation of the $N(1440)$ state was found. Two peaks were observed in the missing-energy, $\omega = E_{\alpha'} - E_\alpha$, distribution (Fig. 1). A large one, in the region of small energy transfers, $\omega \simeq -0.25$ GeV, was evidently due to excitation of the Δ resonance in the projectile α particle, and a smaller one, in the region of $\omega \simeq -0.55$ GeV, was interpreted by Morsch *et al.* [2] as a signal of the Roper resonance excitation in the target

proton. This interpretation was confirmed later by a more detailed theoretical consideration of Hirenzaki *et al.* [10, 11].
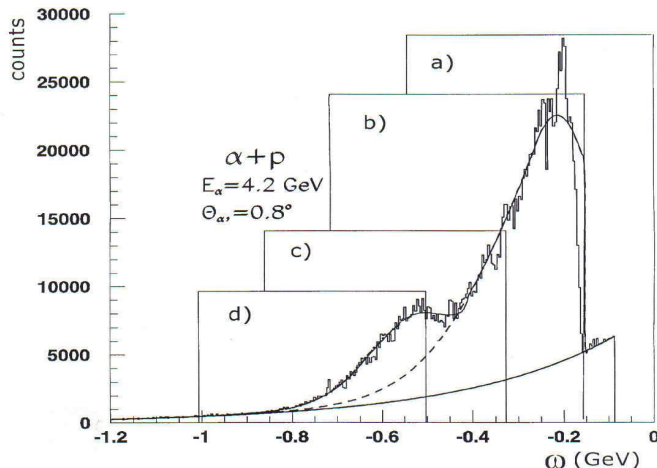

Figure 1: Inclusive missing-energy (ω) spectrum of inelastic αp scattering [2]. The acceptance boundaries of ω for different SPES4 momentum settings in the present experiment are marked as (a), (b), (c) and (d). The mean values of these intervals correspond to $q_{\alpha'}/Z = 3.35$; 3.25; 3.15 and 3.06 GeV/c, respectively.

According to theory [10], only three reaction channels dominate in inelastic αp scattering at this energy. The first one (Fig. 2a) corresponds to excitation of the Δ resonance in the α-particle projectile, while the second and third ones (Figs. 2b,c) correspond to excitation of the Roper (or $N(1520)D_{13}$) resonance in the target proton mainly through exchange of a neutral "sigma meson" (σ). The contribution of other channels is practically negligible. Note that due to the isoscalar nature of the α particle and isospin conservation, direct excitation of the Δ resonance in the proton is forbidden. The final-state products from the $p(\alpha, \alpha')X$ reaction may be either a nucleon (proton or neutron) and one pion, resulting from decay of the Δ or Roper resonances (Fig. 2, diagrams a, b), or a nucleon and two pions, resulting from decay of the Roper resonance (Fig. 2, diagram c).

A drawback of the inclusive αp experiment [2] was that only the momentum of the scattered α particles was measured, while other reaction products were not detected. In order to get more information on the mechanism of the αp-scattering reaction, a semi-exclusive experiment at the Saturne-II accelerator (Saclay) was performed [12], in which the decay products as well as the scattered α were registered.

Here we discuss results of this experiment. The conclusions drawn in this work are based on the missing mass Dalitz plots analysis and on comparisons of the shapes of the experimental spectra with those of the simulated ones.
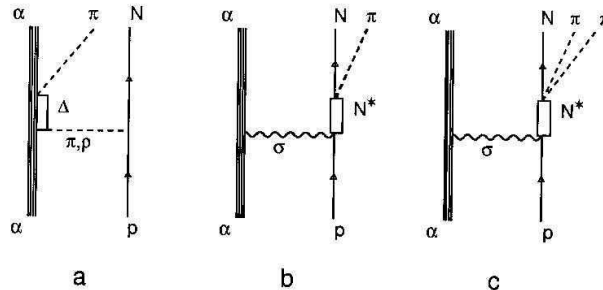
Figure 2: Main diagrams contributing to the $p(\alpha, \alpha')X$ reaction: (a) Δ excitation in the projectile, (b) N^* excitation in the target with the following one-pion $(N\pi)$ decay, and (c) N^* excitation in the target with the following two-pion $(N\pi\pi)$ decay.

2 Experiment

The experimental study of the $p(\alpha, \alpha')X$ reaction discussed in the present paper was carried out at the Saturne-II accelerator beam of α particles with a momentum $q_\alpha = 7$ GeV/c ($E_\alpha = 4.2$ GeV). The scattered α projectiles and the charged products (p, π^+ or π^-) of the reaction were registered with the SPES4-π set-up [13]. The SPES4-π installation included the high-resolution magnetic spectrometer SPES4, which was also used in earlier experiments, and a wide-aperture non-focusing Forward Spectrometer (FS). The last one consisted of an analyzing large-gap dipole magnet, a drift-chamber telescope and a hodoscope of scintillation counters. A liquid-hydrogen target, 60 mm in length, was located inside the analyzing magnet.

The α particles scattered on the liquid-hydrogen target at an angle of $0.8° \pm 1.0°$ were registered with SPES4. The experiment was carried out at four magnetic-rigidity settings of the SPES4 spectrometer. The central values of $q_{\alpha'}/Z = 3.35$, 3.25, 3.15, and 3.06 GeV/c (where $q_{\alpha'}$ is the momentum of the scattered α particle, and $Z = 2$ is the α-particle charge) were chosen, which gave us an opportunity to study the reaction at the energy transfer ω from $- 0.15$ to $- 0.9$ GeV. The ω intervals accepted at different momentum settings of SPES4 in comparison with the results of the inclusive experiment [2] are indicated in Fig. 1. The measurements were performed with the full as well as empty targets. These measurements, properly normalized to the monitor counts, were used to subtract the background from the beam halo and from the beam interaction with the target housing.

The FS allowed to identify the secondary charged particles (p, π^+, or π^-) and to reconstruct their trajectories and momenta. The identification of the particles in the FS was performed on the basis of the energy-loss and time-of-flight measurements [13] by means of the scintillator-counter hodoscope. In the present paper, the data obtained by detecting the scattered α particles with SPES4 and protons or π^+ with the FS are discussed. The measured momenta $\vec{q}$ of the scattered α particle and secondary particles were used to determine the missing mass M_{miss} and the invariant masses $M(N\pi)$ and $M(\alpha'\pi)$ for the one-pion production channel, and $M(N\pi\pi)$ and $M(\alpha'\pi\pi)$ for the two-pion production channel. In the case when protons are detected with the FS, the missing mass M_{miss} is the mass of the object X in the $p(\alpha, \alpha')pX$ reaction, the object X consisting of one or two pions. In the case when π^+-pions are detected with the FS, the missing mass M_{miss} is the mass of the object X in the $p(\alpha, \alpha')\pi^+X$ reaction, the object X consisting of a neutron or a neutron and a π^0-pion. It should be noted that the SPES4-π set-up has a rather high acceptance for registration of events from decay of the Roper resonance (mainly at the momentum settings 3.15 and 3.06 GeV/c), the latter having the Breit-Wigner (BW) resonance mass at about 1440 MeV/c^2 [14]. The SPES4-π set-up and the method of the tracks reconstruction are described in detail in [13].

3 Results and discussion
3.1 Missing mass spectra

The left panel of Fig. 3 presents the distributions of events as a function of the missing mass M_{miss} for the four momentum settings of SPES4 in the cases of π^+ registration by the FS. The spectra include the sums of events from the one-pion and two-pion production channels. For the momentum setting $q_{\alpha'}/Z$ = 3.35 GeV/c, only one peak at $M_{\text{miss}} \simeq M_n = 0.94$ GeV/c^2 corresponding to the mass of the neutron is seen. The width of this peak reflects the experimental resolution of the reconstructed values of M_{miss}. Evidently, this peak contains one-pion events appearing due to decay of Δ excited in the projectile α particle. For the momentum settings $q_{\alpha'}/Z$ = 3.15 and 3.06 Gev/c, contributions of two-pion events (at $M_{\text{miss}} > M_n + M_\pi$) are observed.

The right panel of Fig. 3 presents the distributions of events as a function of M^2_{miss} in the case of proton registration by the FS. It is seen that for the SPES4 setting $q_{\alpha'}/Z$ = 3.35 GeV/c, corresponding to small values of $|\omega|$, a peak at $M^2_{\text{miss}} \simeq 0.02$ (GeV/c^2)^2 (that is at $M_{\text{miss}} \simeq M_\pi = 0.14$ GeV/c^2) dominates in the spectrum. Evidently, this peak is due to one-pion events mostly produced in the decay of the Δ resonance excited in the scattered α particle, as it was discussed before. A slight tail at high masses in this spectrum is presumably due to a small contribution of two-pion events from the low-mass tail of the Roper resonance excited in the proton. The width of the peak at $M^2_{\text{miss}} \simeq 0.02$ (GeV/c^2)^2 reflects the resolution of the reconstructed values of M^2_{miss}.
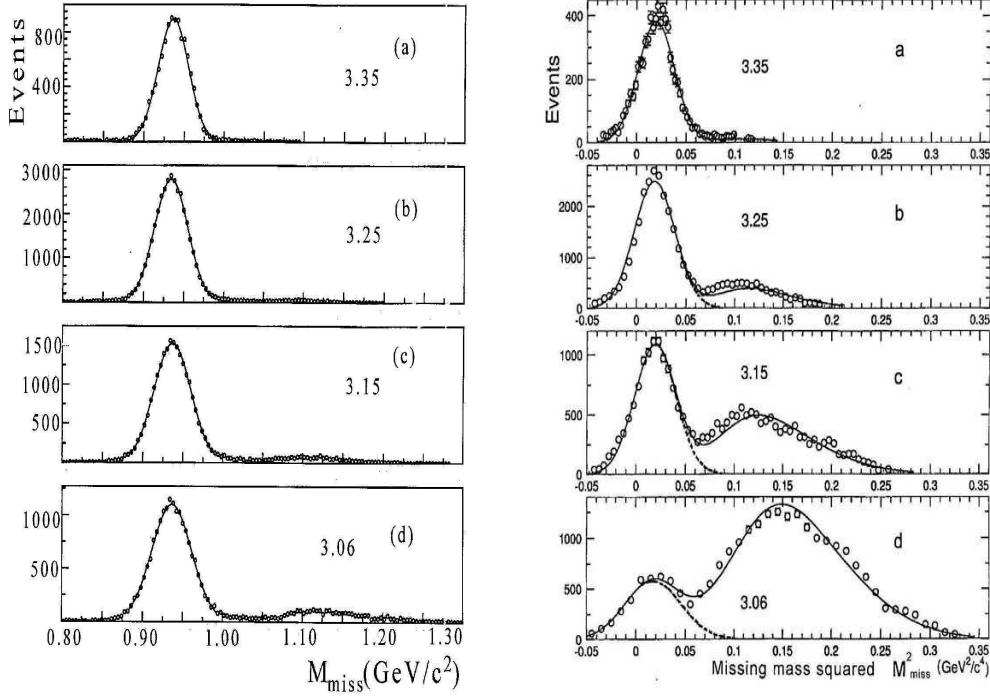
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Figure 3: Missing mass spectra for the $p(\alpha, \alpha')\pi^+ X$ (left panel) and $p(\alpha, \alpha')pX$ (right panel) reactions for the SPES4 momentum settings $q_{\alpha'}/Z = 3.35$ (a), 3.25 (b), 3.15 (c), and 3.06 (d) GeV/c. Dots are experimental points. The distributions of one-pion events are described by Gaussians (solid lines in the left panel, dashed lines in the right panel). The solid lines in the right panel are the sums of the one-pion-production distributions and the simulated two-pion-production distributions normalized to the experimental data.

For the SPES4 momentum setting $q_{\alpha'}/Z = 3.25$ GeV/c, the contribution from two-pion events (at $M^2_{\mathrm{miss}} \geq 0.09$ (Gev/c^2)^2) is more prominent. In the interval of $0.04 \leq M^2_{\mathrm{miss}} \leq 0.09$ (GeV/c^2)^2, one-pion and two-pion events are not resolved. As for the settings $q_{\alpha'}/Z = 3.15$ and 3.06 GeV/c, the data show that the two-pion production is an important channel of the inelastic $p(\alpha, \alpha')pX$ reaction under study. While comparing the numbers of the registered two-pion and one-pion events it should be kept in mind that when we register protons or π^+-pions we select different isospin projections of the studied reaction. Also, the acceptances for detection of one-pion and two-pion events in the considered cases are significantly different. By imposing cuts on the values of M_{miss} (or M^2_{miss}) we can select only one-pion or only two-pion events.
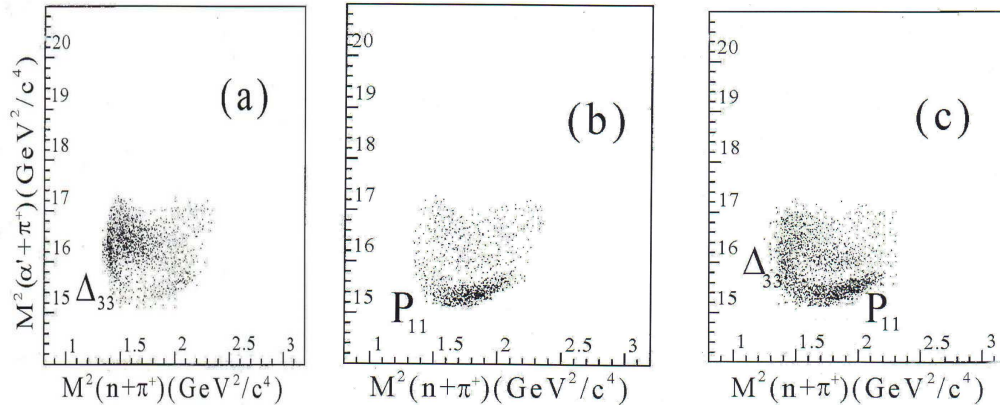
Figure 4: Dalitz plots for the $p(\alpha, \alpha')n\pi^+$ reaction. (a) Simulated events of the Δ resonance decay. (b) Simulated events of the Roper resonance decay. (c) Experimental data. Here and in Fig. 5c, the data of all SPES4 momentum settings, properly normalized, are included.

3.2 One-pion production

Figures 4 and 5 present the Dalitz plots of one-pion events for the cases when pions (Fig. 4) and when protons (Fig. 5) are registered with the FS. Comparing the Dalitz plots of the experimental data (Fig. 4c and Fig. 5c) with the Dalitz plots of the simulated events (Figs. 4a,b and Figs. 5a,b) we see that the events in the spots where the experimental points are concentrated in the Dalitz plots correspond to the simulated events from the decay of the Δ and Roper resonances. Moreover, the positions of these spots in the Dalitz plots tell us (in agreement with theory) that the Roper resonance is excited in the target proton, whereas the Δ resonance is excited in the projectile α particle. In particular, the positions of the maxima in the $M^2(N\pi)$ spectra (as follows from Figs. 4c and 5c) for the Roper events are approximately the same in the cases when pions and when protons are registered, as it should be for the Roper resonance excitation in the target proton. On the other hand, the positions of the maxima in the $M^2(\alpha'\pi)$ spectra in these two cases are very different, which proves that the Roper resonance is excited not in the projectile α particle (but it is excited in the target proton). Some depletion of events in Fig. 5c in the region of $M^2(p\pi^0)$ $\approx 1.3 \div 1.4$ $(\text{GeV}/c^2)^2$ and $M^2(\alpha'\pi^0) \approx 17 \div 18$ $(\text{GeV}/c^2)^2$ can be interpreted as an indication of a destructive interference between the processes of one-pion production through excitation and decay of the Roper and delta resonances. Note that according to theoretical considerations of Hirenzaki et $al.$ [10] the interference between these processes gives a negative contribution to the cross section.
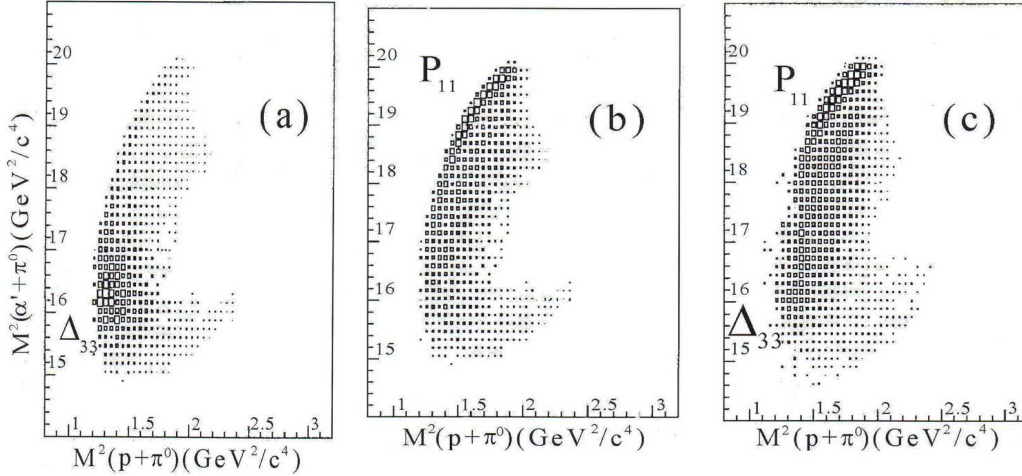
Figure 5: Dalitz plots for the $p(\alpha, \alpha')p\pi^0$ reaction. (a) Simulated events of the Δ resonance decay. (b) Simulated events of the Roper resonance decay. (c) Experimental data.

3.3 Two-pion production: excitation of the Roper resonance

Now we turn to the channel of two-pion production in the case when protons are registered with the FS. It is evident that the two-pion events are not from the decay of a Δ resonance, for which the branching for the two-pion decay mode is very small. We can assume that the detected two-pion events are due to excitation and decay of the Roper resonance in the target proton. In order to check this conjecture, we have simulated the spectra of the invariant squared masses $M^2(\alpha'\pi\pi)$ and $M^2(p\pi\pi)$ for the $p(\alpha, \alpha')p\pi\pi$ reaction and compared them with the experimental data. The simulation calculations of these spectra, as well as of the Dalitz plots discussed previously, were performed with the phase space for the considered reactions including the Roper and Δ resonances described by the modified BW distribution with the mass-dependent resonance widths according to Eqs. (9) and (11) of [15]. (We assumed the mass dependence of the Roper-resonance width for two-pion decay to be the same as that for one-pion decay.) The α form factor, calculated using the parameterization of [3], and the SPES4-π acceptance were also taken into account. The resonance masses and widths of the Roper and Δ resonances were taken from a PDG review [14]. To exclude a possible contribution of one-pion events to the considered experimental spectra, only the events with $M^2_{\mathrm{miss}} \geq 0.09$ $(\mathrm{GeV}/c^2)^2$ were used. A similar cut was also imposed on the simulated spectra. The shapes of the simulated spectra are in satisfactory agreement with those of the data, as it is demonstrated in Fig. 6 for the SPES4 momentum setting $q_{\alpha'}/Z = 3.06$ GeV/c. Similar results were also obtained for the setting $q_{\alpha'}/Z = 3.15$ GeV/c. Note that no fitting parameters
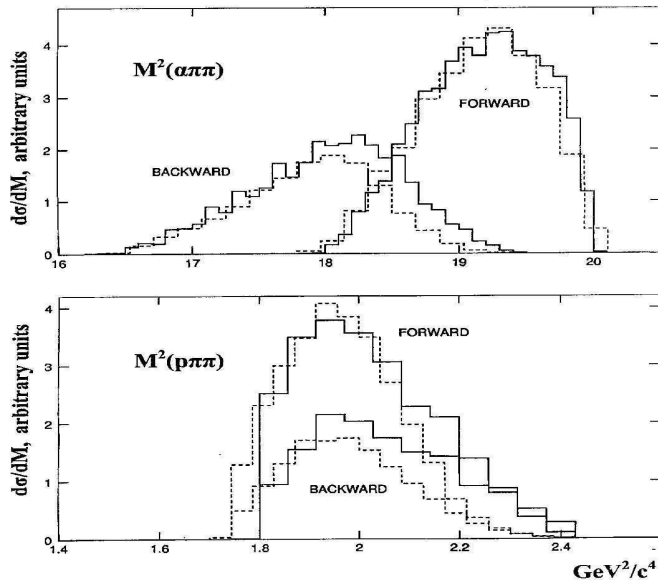
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Figure 6: Comparison of the simulated invariant-mass-squared $M^2(\alpha'\pi\pi)$ and $M^2(p\pi\pi)$ distributions (dashed line) with the distribution obtained from the experimental data (solid line) for the $p(\alpha, \alpha')p\pi\pi$ reaction for the forward and backward emitted protons in the N^* centre-of-mass system at $q_{\alpha'}/Z = 3.06$ GeV/c. The MC simulations are performed assuming Roper excitation in the target.

were used in these calculations, the Roper resonance parameters, as it was said, being taken from [14]: $M_R = 1440$, $\Gamma_R = 350$ MeV/c^2.

In principal, two pions might be produced in αp scattering via intermediate-state excitation of the Roper resonance in the projectile α particle, or double Δ excitations, either both Δ's in the α particle, or one Δ in the target proton and one Δ in the α particle. We have simulated such events. The shapes of the simulated spectra for these reaction channels do not agree with those of the experimental data (see [12]). We remind that according to theory [10] the contributions from these channels are rather small, and they may be neglected. Figure 7 presents a comparison of the simulated spectra of the invariant mass $M(p\pi\pi)$ with the corresponding experimental spectrum obtained from the properly combined data of the SPES4 momentum settings $q_{\alpha'}/Z = 3.25$, 3.15 and 3.06 GeV/c. In these simulations, several BW Roper-resonance parameters were used: from [14], [3] and [16]. One can see (Fig. 7a) that the simulated spectrum of $M(p\pi\pi)$ is in reasonable agreement with the experimental data when the standard Roper parameters are assumed ($M_R = 1440$, $\Gamma_R = 350$ MeV/c^2 [14]). (Due to influence of the α form factor the maxima in the simulated $M(p\pi\pi)$ distributions are shifted to the masses smaller than the values of the resonance masses used in the simulations.) The results of the simulation with the Roper parameters from [3] ($M_R = 1390$, $\Gamma_R = 190$ MeV/c^2) are in somewhat worse agreement with the data
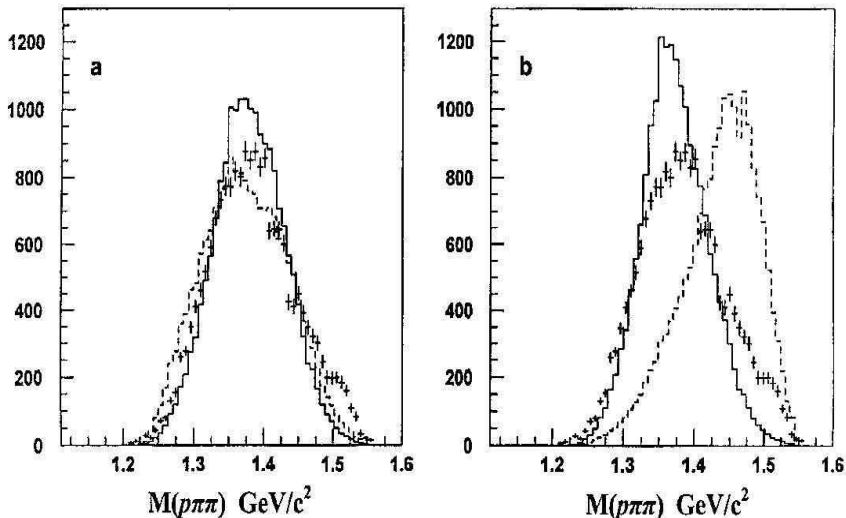
Figure 7: Comparison of the simulated invariant-mass distributions $M(p\pi\pi)$ (solid, dashed and dotted lines) with the experimental one (crosses) obtained from the data of the 3.06, 3.15 and 3.25 GeV/c SPES4 momentum settings. Fig. 7a: dashed line – phase-space calculations, solid line – Roper excitation with $M_R = 1440$, $\Gamma_R = 350$ MeV/c^2 [14]. Fig. 7b: solid line – Roper excitation with $M_R = 1390$, $\Gamma_R = 190$ MeV/c^2 [3], dotted line – Roper excitation with $M_R = 1485$, $\Gamma_R = 284$ MeV/c^2 [16], dashed line – $N(1520)D_{13}$ excitation with $M_D = 1520$, $\Gamma_D = 120$ MeV/c^2 [14]. The simulated spectra are normalized to the experimental one.

(see Fig. 7b). However, in view of not sufficient precision of the data and due to some uncertainties in the performed analysis, in particular due to an uncertainty in the possible contribution of the higher-mass $N(1520)D_{13}$ resonance, our data analysis does not allow us to give preference to one of these considered sets of the Roper parameters. As for the $M(p\pi\pi)$ distribution simulated with the Roper parameters from [16] ($M_R = 1485$, $\Gamma_R = 284$ MeV/c^2), it is in noticeable disagreement with our data (see Fig. 7b). According to a very recent partial-wave analysis of Sarantsev et $al.$ [17], the BW Roper-resonance parameters are: $M_R = 1436 \pm 15$, $\Gamma_R = 335 \pm 40$ MeV/c^2. On the other hand, the new data of the BES collaboration on the J/ψ decay [18] and of the CELSIUM-WASA collaboration on the pion production in pp collisions [19] are in favour of smaller values of the Roper mass and width: $M_R \simeq 1360$, $\Gamma_R \simeq 150$ MeV/c^2.

We have also performed a simulation under an assumption that two-pion events are produced via excitation and decay only of the $N(1520)D_{13}$ resonance. In this case, the results of the simulations are in drastic disagreement with the data (Fig. 7b). At the same time, it is seen that a small admixture of events from this resonance to events from the Roper decay is possible. Adding to the

simulated spectrum $M(p\pi\pi)$ a small contribution of events from the decay of the $N(1520)D_{13}$ resonance can improve the agreement of the simulated spectrum with the data in the region of high masses ($M(p\pi\pi) \simeq 1.5$ GeV/c^2). According to our estimation, the contribution of events from the $N(1520)D_{13} \to p\pi\pi$ decay in the analyzed data may be about $10 \div 20\%$.

Thus, we see that our data are consistent with the scenario that two-pion events are produced mostly via excitation in the target proton of the Roper resonance (with the mass of about $1390 \div 1440$ MeV/c^2), which decays to a proton and two pions. It should be admitted however that the shape of the simulated $M(p\pi\pi)$ spectrum is also consistent with the data for the case of non-resonant two-pion production (see Fig. 7a), the difference between the shapes of the $M(p\pi\pi)$ distributions for the non-resonant case and the resonant one (with the Roper parameters from PDG) being relatively small. This may be explained by the fact that the width of the Roper resonance is large (as in PDG) and its propagator exerts little influence on the shape of the simulated $M(p\pi\pi)$ spectrum. An estimate of the non-resonant contribution has been made by Alvarez-Ruso *et al.* [20] for the case of inelastic pp scattering at 1 GeV. It was shown that the non-resonant contribution should be about two orders smaller than the resonant one. The same should be also for αp scattering. Therefore, the non-resonant contribution may be neglected. Taking this statement for granted, and taking into account our previous considerations, we conclude that the $p(\alpha, \alpha')p\pi\pi$ reaction (at an energy of ~ 1 GeV/nucleon) proceeds mainly through the intermediate state which is the Roper resonance excited in the target proton. Due to the isoscalar nature of the α particle, the Roper resonance, as has been already mentioned, may be excited in this reaction via an exchange between the projectile α particle and the target proton of a σ meson, which is a coupled pion pair in the isospin $I = 0$, S-wave state (Fig. 2c).

3.4 Two-pion production: decay of the Roper resonance

In πN scattering (see [14]), the two-pion decay of the Roper resonance occurs mainly either as simultaneous emission of two pions in the $I = 0$ isospin, S-wave state, $N^* \to N(\pi\pi)^{I=0}_{S-wave}$, or as sequential decay through the Δ resonance, $N^* \to \Delta\pi \to N\pi\pi$, with branching ratios of $\sim 10\%$ and $\sim 30\%$, respectively. Manley *et al.* [4, 5] performing a partial-wave analysis of the $\pi N \to N\pi$ & $N\pi\pi$ scattering data introduced a σ meson (or ϵ in the notation of [21]) as an S-wave isoscalar $\pi\pi$ interaction. In the present analysis, we follow Manley's approach to the two-pion decay of the Roper resonance and also consider two possible channels of the Roper decay, one through the Δ resonance and another one through the σ meson (Fig. 8).

As follows from theory [21], the shape of the spectra of the invariant mass $M(\pi\pi)$ of the pions emitted in the Roper-resonance decay is essentially different for these two channels. Therefore, a comparison of our experimental data with theoretical
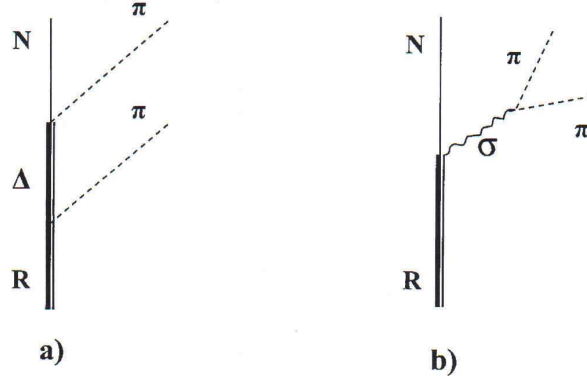
Figure 8: Diagrams for the Roper-resonance decay with emission of two pions in Manley's approach according to [21]. (a) Decay through the intermediate Δ state, $N^* \to \Delta\pi \to N\pi\pi$. (b) Decay through the intermediate σ-meson state, $N^* \to N\sigma \to N\pi\pi$.

predictions can be used to find out which process is more important for decay of the Roper resonance excited in αp inelastic scattering. In πN scattering, according to [14], a sequential Δ decay (Fig. 8a) is dominant. On the other hand, as Morsch and Zupranski discussed [3], the breathing mode of the nucleon is strongly excited in αp scattering, and a different decay pattern (dominated by that shown in Fig. 8b) is expected.

In Fig. 9, the simulated $M^2(\pi\pi)$ spectra are compared with the experimental data for the SPES4 momentum settings $q_{\alpha'}/Z = 3.06$ and 3.15 GeV/c, which have high acceptance for events of the $p(\alpha, \alpha')p\pi\pi$ reaction. The experimental spectra $M^2(\pi\pi)$ are obtained from the missing-mass-squared M^2_{miss} spectra shown in Fig. 3 (right panel) by subtracting the $M^2(\pi)$ contributions of the one-pion-production channels, the $M^2(\pi)$ spectra being parameterized by Gaussians (see dashed curves in Fig. 3). In these simulations, the Roper, σ and Δ BW shapes, the α form factor, and the SPES4-π acceptance were taken into account. Further, the simulated spectra were smeared to take into account the experimental resolution of $M^2(\pi\pi)$, which was estimated from the width of the $M^2(\pi)$ spectra. We have checked that an uncertainty in the α form factor used affects the shape of the simulated spectra only insignificantly. The following parameters for the Δ resonance and σ meson were used: $M_\Delta = 1232$, $\Gamma_\Delta = 120$ MeV/c^2 [14], and $M_\sigma = 600$, $\Gamma_\sigma = 600$ MeV/c^2 [22]. It should be noted that in the case of decay through the intermediate σ meson, the specific parameters of this meson exert practically no influence on the simulated spectra due to the large value of Γ_σ. As for the channel of decay through the intermediate Δ-resonance state, the amplitude of this process is strongly influenced by the following kinematical factor (see [21]):

$$A(\vec{q}_{\pi_1}, \vec{q}_{\pi_2}) \sim (\vec{q}_{\pi_1} \cdot \vec{q}_{\pi_2}), \tag{1}$$

where $\vec{q}_{\pi_1}$ and $\vec{q}_{\pi_2}$ are the pion momenta in the N^* centre-of-mass system. We

have not included small spin-dependent terms in Eq. (1). According to [23, 24], the contribution of these spin-dependent terms is about 16 times smaller than that of the $\vec{q}_{\pi_1} \cdot \vec{q}_{\pi_2}$ term, and to a good approximation it can be neglected. As a result of the factor $A(\vec{q}_{\pi_1}, \vec{q}_{\pi_2})$, the simulated spectra of $M^2(\pi\pi)$ have two maxima, one near the minimum values of $M(\pi\pi)$ (at $M(\pi\pi)$ close to 0.3 GeV/c^2) and another one at larger values of $M(\pi\pi)$ (close to 0.45 GeV/c^2). The first peak corresponds to the events when both emitted pions fly in the N^* centre-of-mass system with similar momenta in the same direction, while the second peak corresponds to the events when the pions are emitted in opposite directions.
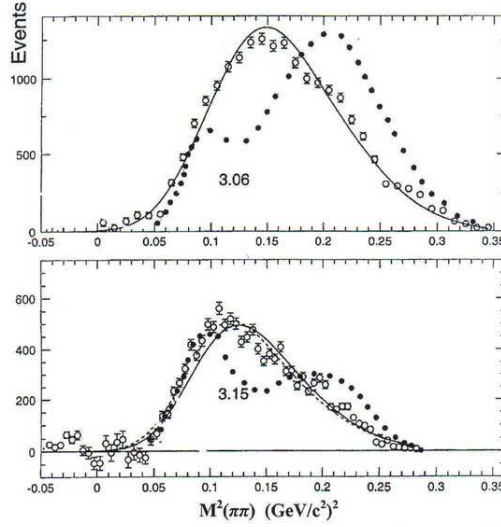

Figure 9: Invariant-mass-squared $M^2(\pi\pi)$ distributions for the $p(\alpha, \alpha')p\pi\pi$ reaction. Open points – experimental data. Solid curves – results of the MC simulations assuming the $N^* \to p\sigma \to p\pi\pi$ decay. Dotted curves – results of the MC simulations assuming the $N^* \to \Delta\pi \to p\pi\pi$ decay. Dashed line in the lower plot – result of the MC simulation assuming the $N^* \to p\sigma \to p\pi\pi$ decay with a small admixture of events from the $N^* \to \Delta\pi \to p\pi\pi$ decay.

As one can see in Fig. 9, the shapes of the $M^2(\pi\pi)$ spectra simulated for the channel of the Roper resonance decay through the Δ resonance are in evident disagreement with the experimental data for both SPES4 momentum settings. As opposed to this, the shape of the simulated spectrum $M^2(\pi\pi)$ assuming the decay through the intermediate σ meson is in perfect agreement with the data for the SPES4 setting $q_{\alpha'}/Z = 3.06$ GeV/c. A similar spectrum for the SPES4 setting $q_{\alpha'}/Z = 3.15$ GeV/c is also in fairly good agreement with the data[1]. Thus, the $M^2(\pi\pi)$ spectra measured in this experiment suggest that the Roper

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[1]Better agreement with the data can be achieved in this case (see Fig. 9) if a small admixture of events corresponding to the Roper decay through the intermediate state of the Δ resonance is added to the simulated spectrum.
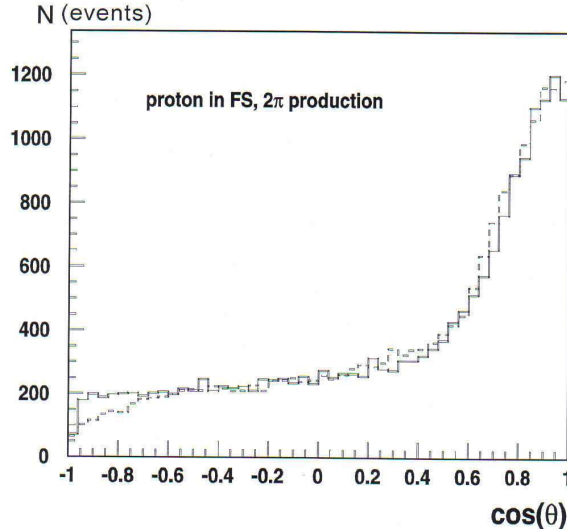
Figure 10: Angular distribution of the emitted protons in the N^* centre-of-mass system, not corrected for the SPES4-π acceptance. Angle θ is the angle between the proton momentum and the momentum transfer $\vec{q}_\alpha - \vec{q}_{\alpha'}$ in the rest frame of N^*. The solid line shows the experimental data, the dashed line is the normalized Monte Carlo simulation, made by assuming isotropic N^* decay. (The simulated spectrum, as well as the experimental one, is distorted by the SPES4-π acceptance.)

resonance excited in the $p(\alpha, \alpha')p\pi\pi$ reaction at an energy of ~ 1 GeV/nucleon decays mainly as $N^* \rightarrow p\sigma \rightarrow p\pi\pi$.

This conclusion is also supported by the extracted angular distribution of the emitted protons in the N^* centre-of-mass system. The obtained distribution agrees with the isotropic decay of N^* (see Fig. 10), and therefore it agrees with the assumed picture of decay of the Roper resonance (with the spin 1/2) to a nucleon and a scalar meson.

Our conclusion that the two-pion decay of the Roper resonance excited in αp scattering at 1 GeV/nucleon proceeds predominantly through the $N^* \rightarrow p\sigma \rightarrow p\pi\pi$ channel is very different from previous πN-scattering-analyses results [14]. On the other hand, our result nicely correlates with recent investigations of the two-pion production in pp inelastic-scattering experiments at energies of $0.65 \div 1.45$ GeV [25]. The authors of these studies come to the conclusion that the two-pion production in pp scattering at the considered energies proceeds mainly via excitation of the Roper resonance, which decays predominantly through an intermediate σ meson. Sarantsev *et al.* [17] who performed a combined partial-wave analysis of several pion-production reactions also conclude that the channel of the Roper decay through the σ meson is rather important, the contribution of this channel being about three times larger than that given by PDG [14]. The importance of the σN channel of the Roper decay was pointed out in several

theoretical papers. In particular, Dillig and Scott [26], considering the Roper resonance in the constituent quark-gluon model, came to the conclusion that the wave function of the Roper resonance contains a very strong, $\simeq 50\%$, component of a σ-meson field. Consequently, the σN decay channel should dominate in the two-pion decay of the Roper resonance. Similar statements that the σN channel of the Roper decay is more important than the $\pi\Delta$ channel, were also made by Kukulin *et al.* [27], Krehl *et al.* [28], and some others.

As it was discussed by Morsch and Zupranski [3], the contribution of the channel with the σ meson can be different in different two-pion-production reactions. Evidently, the properties of the Roper resonance and the role of the σ meson in pion-production reactions need further studies.

4 Conclusions

The one-pion and two-pion production $p(\alpha, \alpha')X$ reaction has been studied in a semi-exclusive experiment at the Saturne-II accelerator at an energy of $\simeq$ 1 GeV/nucleon with the detection of the scattered α particle and the secondary pion or proton. The results of the measurements are qualitatively compared with the simulated Dalitz plots and invariant-mass spectra based on the predictions of the Oset-Hernandez model using Manley's approach to the Roper decay. The obtained results show that the one-pion production in this reaction occurs via decay of the Δ resonance excited in the projectile α particle as well as decay of the Roper resonance excited in the target proton. The two-pion production occurs via decay of the Roper resonance excited in the target proton, the dominant channel of the Roper decay being $N^* \to N\sigma \to N\pi\pi$. The obtained results are in favour of the statement that the resonance excited in αp scattering at the excitation energy around 1440 MeV is the breathing-mode excitation of the nucleon.

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