Two-pion production in αp scattering at 1 GeV/nucleon in the energy region of the Roper resonance excitation

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Semiexclusive measurements of the two-pion-production $p(\alpha,\alpha')p\pi\pi$ reaction have been carried out at an energy of $E_\alpha = 4.2$ GeV at the Saturne-II (Saclay) accelerator with the SPES4-π installation. This reaction was investigated by simultaneous registration of the scattered α particle and the secondary proton. The obtained results show that the two-pion production in inelastic α-particle scattering on the proton at the energy of the experiment proceeds mainly through excitation in the target proton of the Roper resonance and its decay with emission of two pions in the isospin $I = 0$, S-wave state.

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I. 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 and co-workers [2,3] have interpreted the scalar excitation of the $N(1440)P_{11}$ state in αp scattering as the breathing-mode ($L = 0$) monopole excitation of the nucleon. In this interpretation, the $N(1440)P_{11}$ 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 [4], in three-body nuclear forces [5], and in the swelling of nucleons in nuclei [6]. The investigation of the $N(1440)P_{11}$ resonance was the goal of numerous theoretical (see, e.g., Refs. [7–13] and references therein) and experimental [14–16] studies. This activity was motivated by the still not properly understood nature of the resonance, its relatively low mass, and the anomalously large width of a few hundred MeV.

The Roper resonance was observed and studied for the first time in πp partial-wave analyses [1,17–20]. 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 $\pi N-$, αp-, and γp-scattering experiments, with the conclusion that the $N(1440)P_{11}$ 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 Δ resonance. The first structure is strongly excited by scalar probes, as in αp scattering, whereas the second one is excited in spin-isospin-flip reactions, as in πN scattering. The two-resonance picture of $N(1440)P_{11}$ and the breathing-mode excitation of the proton were also discussed by the same authors [21] 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 [22]. Because of the composite structure of the α particle, the mechanism of reactions with α particles is of course more complicated than that when only elementary particles are involved. In particular, the invariant-mass spectra observed in αp scattering are significantly distorted by the α form factor, which should be taken into account in the data analysis.

Inelastic αp scattering was investigated previously at $E_\alpha = 4.2$ GeV in an inclusive experiment [2] at the Saturne-II accelerator in Saclay by using the SPES4 magnetic spectrometer [23]. The energy distribution of the scattered α particles from the $p(\alpha,\alpha')X$ reaction was studied, and a strong excitation of the $N(1440)P_{11}$ 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 $\Delta(1232)P_{33}$ (Δ) resonance in the projectile α particle, and a smaller

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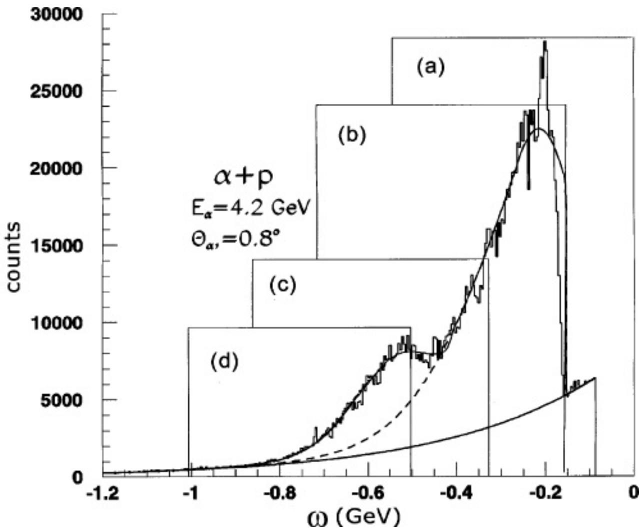

FIG. 1. Inclusive missing-energy (ω) spectrum of inelastic αp scattering [2]. The acceptance boundaries of ω for different SPES4 momentum settings in the present experiment are marked as (a), (b), (c), and (d). The mean values of these intervals correspond to $q_{\alpha'}/Z = 3.35$, 3.25, 3.15, and 3.06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

one, in the region of $\omega \simeq -0.55$ GeV, was interpreted by Morsch *et al.* [2] as a signal of the $N(1440)P_{11}$ excitation in the target proton. This interpretation was confirmed later by a more detailed theoretical consideration of Hirenzaki and co-workers [24,25].

According to theory [24], only three diagrams (Fig. 2) dominate in inelastic αp scattering at this energy. The first diagram [Fig. 2(a)] corresponds to excitation of the Δ resonance in the α-particle projectile, whereas the second and third diagrams [Figs. 2(b) and 2(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) [26,27] between the α particle and the proton. The contribution of other possible diagrams is practically negligible. Note that owing to the isoscalar nature of the α particle and isospin conservation, direct excitation of the Δ resonance in the proton is forbidden [24]. 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 [Figs. 2(a) and 2(b)], or a nucleon and two pions, resulting from decay of the Roper resonance [Fig. 2(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. To get more information on the resonance excitation and its decay in the αp-scattering reaction, an exclusive (or semiexclusive) experiment at the Saturne-II accelerator (Saclay) was proposed [28], in which the decay products as well as the scattered α would be measured. The channel of the one-pion Roper resonance decay strongly interferes with that of decay of Δ, the latter decaying in practically pure one-pion decay mode [29]. This interference turns the separation of the channel of one-pion Roper decay from the channel of decay of Δ into a complicated task. For the two-pion decay channel of the Roper resonance, the contributions of other possible channels of two-pion production and interference with them are expected to be small, which allows one to extract much less ambiguous results.

In this paper we present the results of the experiment with respect of the two-pion-production reaction. We do not discuss the absolute cross-section measurements. The conclusions drawn in this work are based on comparisons of the shapes of the simulated spectra with the experimental ones.

II. EXPERIMENT

The experimental study of the $p(\alpha, \alpha')p\pi\pi$ reaction discussed in this 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 setup [30]. The SPES4-π installation (Fig. 3) included the high-resolution magnetic spectrometer SPES4 [23], which was also used in earlier experiments (see, e.g., Refs. [2,31]), and a wide-aperture nonfocusing forward

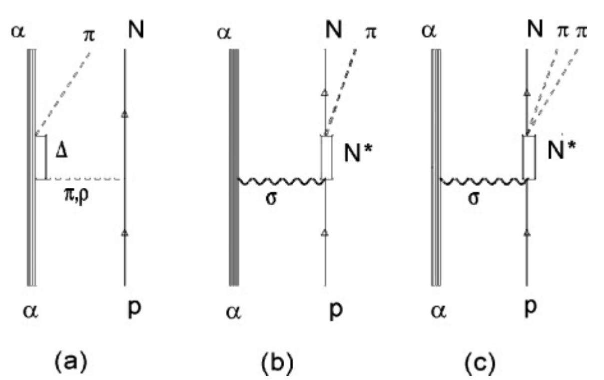

FIG. 2. Main diagrams contributing to the $p(\alpha, \alpha')X$ reaction: (a) Δ excitation in the projectile, (b) N^* excitation in the target with the following one-pion ($N\pi$) decay, and (c) N^* excitation in the target with the following two-pion ($N\pi\pi$) decay.

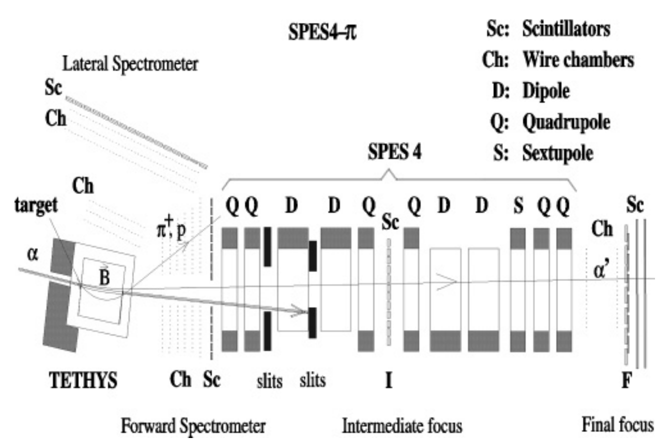

FIG. 3. Schematic view of the SPES4-π setup. TETHYS: dedicated large-gap dipole magnet; D, Q, and S: magnetic elements of the SPES4 spectrometer; Ch: multiwire drift chambers; Sc: scintillator-counter hodoscopes.

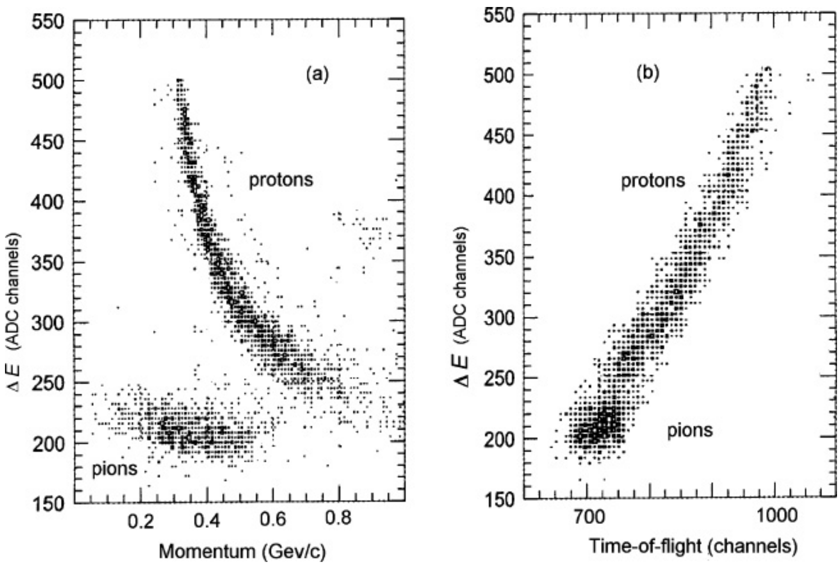

FIG. 4. Energy loss ΔE (in ADC channels) vs particle momentum (a) and energy loss against TOF correlation (b) for secondary charged particles (protons and pions) from the $p(\alpha, \alpha')X$ reaction for the SPES4 momentum setting 3.06 GeV/c.

spectrometer (FS) [30]. The FS consisted of an analyzing large-gap dipole magnet TETHYS, a drift-chamber telescope, and a hodoscope of scintillation counters. A liquid-hydrogen (LH_2) target, 60 mm in length, was located inside the TETHYS magnet.

The α particles scattered on the hydrogen target at an angle of $0.8^\circ \pm 1.0^\circ$ 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 are indicated in Fig. 1. The measurements were performed with the full LH_2 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 us 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 (ΔE) and time-of-flight (TOF) measurements by means of the scintillator-counter hodoscope. An example of the obtained results is demonstrated in Fig. 4(a), which presents the energy loss of the registered secondary particles (protons and pions) versus their momenta. It is seen that in the momentum range of $0.25 \leqslant q_{p,\pi} \leqslant 0.80$ GeV/c the values of ΔE for protons are significantly larger than those for pions, and so the registered protons could be easily separated from the pions. Figure 4(b) presents the correlation between ΔE and TOF. In this figure, the registered pion events are located in the spot with the minimum values of ΔE and TOF. Choosing the analyzed events in the limited region of their ΔE-TOF correlation allowed us to reduce significantly the number of background events.

The FS possessed high acceptance for detection of the scattered (secondary) protons emitted in the studied reaction predominantly in the forward direction. In this paper, the data obtained by detecting the scattered α particles with SPES4 and only protons with the FS are discussed. The measured momenta $\mathbf{q}_{\alpha'}$ and $\mathbf{q_p}$ of the scattered α particle and secondary proton were used to determine the missing mass $M_{\rm miss}$ and the invariant masses $M(p\pi\pi)$ and $M(\alpha\pi\pi)$. The missing mass $M_{\rm miss}$ is defined in the present paper as the mass of the object X in the $p(\alpha, \alpha')pX$ reaction, with the object X consisting of one or two pions. The number of the emitted pions could be, in principle, more than two. However, the probability to have three (or four) pions in this reaction at the considered energy is expected to be very small. The results of Monte Carlo simulations of the SPES4-π acceptance (when α particles are detected with SPES4 and protons are detected simultaneously with the FS) as a function of the calculated invariant mass $M(p\pi\pi)$ are shown in Fig. 5. These simulations were performed by assuming a pure phase space for the

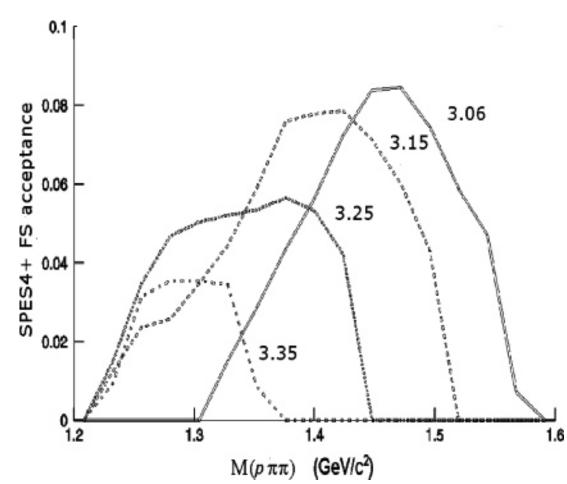

FIG. 5. Acceptances of the SPES4-π spectrometer for the $p(\alpha, \alpha')p\pi\pi$ reaction at different SPES4 momentum settings vs the invariant mass $M(p\pi\pi)$. The SPES4-π acceptance is defined here as the ratio of the number of the events accepted by SPES4-π to that of the simulated events in the same unit interval of $M(p\pi\pi)$.

TABLE I. SPES4-π installation main parameters.

SPES4	Angular acceptance, $\Delta\theta_x$	35 mrad
	Angular acceptance, $\Delta\theta_y$	46 mrad
	Momentum resolution, $\delta q/q$	0.8%
FS	Angular acceptance, $\Delta\theta_x$	0.9 rad
	Angular acceptance, $\Delta\theta_y$	0.3 rad
	Angular resolution, $\delta\theta_x$, $\delta\theta_y$	0.02 rad
	Momentum resolution, $\delta q/q$ (at $q_p = 0.8$ GeV/c)	∼4%

$p(\alpha, \alpha')p\pi\pi$ reaction and taking into account the α-particle form factor and the geometrical acceptance of the setup. One can see that the SPES4-π setup has a rather high acceptance for registration of events from decay of the Roper resonance, the latter having the Breit-Wigner (BW) resonance mass at about 1440 MeV [29]. The main parameters of the SPES4-π installation are presented in Table I. The SPES4-π setup and the method of the tracks reconstruction are described in detail in Ref. [30].

III. RESULTS AND DISCUSSION

A. Intermediate-state excitation

Two-pion and one-pion events were separated in the analysis of the experimental data by making use of the determined values of the squared missing mass, $M^2_{\rm miss}$. Figure 6 presents the distributions of $M^2_{\rm miss}$ for the four momentum settings of SPES4. The spectra include the sums of events from the one-pion and two-pion production channels. It is seen in Fig. 6(a) that for the SPES4 setting $q_{\alpha'}/Z = 3.35$ GeV/c, corresponding to small values of $|\omega|$ (see Fig. 1), a peak at $M^2_{\rm miss} \simeq 0.02$ (GeV/c^2)^2 (i.e., at $M_{\rm miss} \simeq 0.14$ 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 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. A fraction of the tail could also be due to an instrumental effect. According to our estimate, such a tail of background events may be at the level of 1% or less of the one-pion peak height. The width of the peak at $M^2_{\rm miss} \simeq 0.02$ (GeV/c^2)^2 reflects the resolution of the reconstructed values of $M^2_{\rm miss}$. The shape of this peak was found to be close to Gaussian.

For the SPES4 momentum setting $q_{\alpha'}/Z = 3.25$ GeV/c, the contribution from two-pion events [at $M^2_{\rm miss} \geqslant 0.09$ (Gev/c^2)^2] is more prominent [Fig. 6(b)]. In the interval of $0.04 \leqslant M^2_{\rm miss} \leqslant 0.09$ (GeV/c^2)^2, one-pion and two-pion events are not resolved. For the settings $q_{\alpha'}/Z = 3.15$ GeV/c and $q_{\alpha'}/Z = 3.06$ GeV/c, the data show [Figs. 6(c) and 6(d)] 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 the acceptance for detection of two-pion events in our experiment is higher than that for detection of one-pion events. This is so because the protons to be detected by the FS are emitted in the forward direction in a narrower angular cone for the two-pion channel in comparison with the one-pion channel. Note also that the detected one-pion events are from the reaction $p(\alpha, \alpha')p\pi^0$, whereas the two-pion events are from the reactions $p(\alpha, \alpha')p\pi^0\pi^0$ and $p(\alpha, \alpha')p\pi^+\pi^-$, the last two channels not being separated in this study.

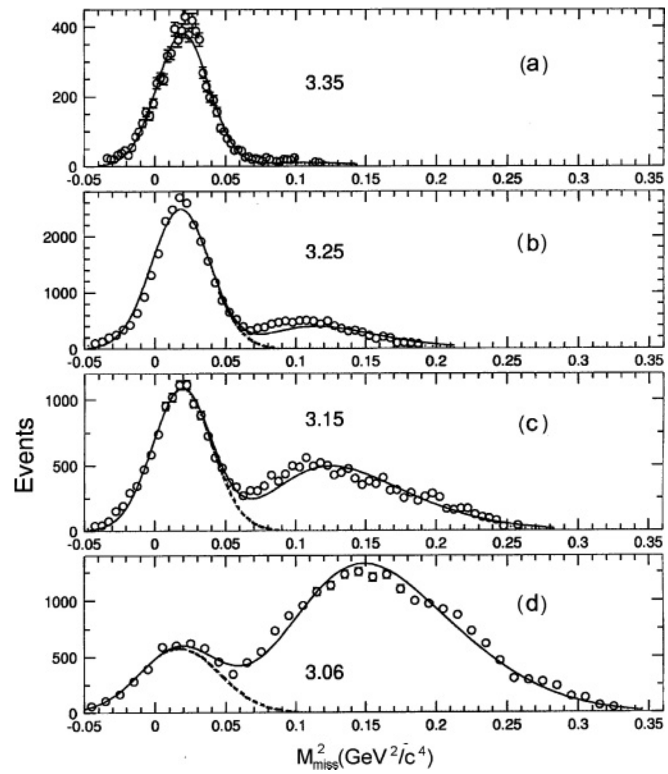

FIG. 6. Missing-mass-squared, $M^2_{\rm miss}$, spectra for the $p(\alpha, \alpha')pX$ reaction for different SPES4 momentum settings $q_{\alpha'}/Z =$ 3.35 GeV/c (a), 3.25 GeV/c (b), 3.15 GeV/c (c), and 3.06 GeV/c (d). The open points are the experimental data. The solid lines are the sums of the one-pion-production distributions parametrized by Gaussians (dashed lines) and the two-pion-production distributions calculated by taking into account the $p(\alpha, \alpha')p\pi\pi$ phase space, α-particle form factor [3], and SPES4-π acceptance.

We can assume that the detected two-pion events are due to excitation and decay of the Roper resonance in the target proton. 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 following possible channels (Fig. 7) of the $p(\alpha, \alpha')p\pi\pi$ reaction were simulated: Roper excitation in the target proton, Roper excitation in the projectile α particle, double Δ excitations in the α particle, and simultaneous Δ excitations in the proton and α particle (one Δ in the proton and one Δ in the α particle). The simulation calculations were performed with the phase space for the $p(\alpha, \alpha')p\pi\pi$ reaction 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 Ref. [32]. (We assumed the mass dependence of the Roper resonance width

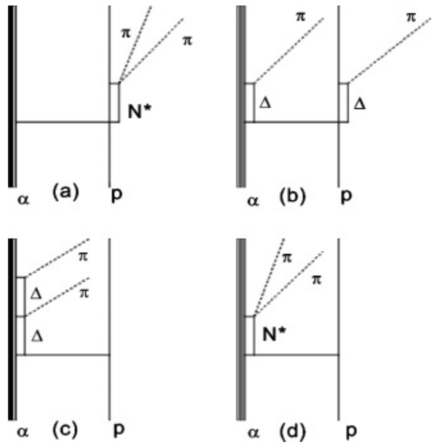

FIG. 7. Possible channels of the $p(\alpha, \alpha')p\pi\pi$ reaction: (a) N^* excitation in the target, (b) two Δ excitations, one in the projectile and one in the target, (c) consecutive double Δ excitations in the projectile, and (d) N^* excitation in the projectile.

for two-pion decay to be the same as that for one-pion decay.) The α form factor, calculated by using the parametrization of Ref. [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 [29]. To exclude a possible contribution of one-pion events to the considered experimental spectra, only the events with $M^2_{\rm miss} \geqslant 0.09$ (GeV/c^2)^2 were used. A similar cut was also imposed on the simulated spectra.

It is evident that the simulations are rather sensitive to the assumed mechanism of the reaction. Indeed, the results shown in Fig. 8 are significantly different for the considered reaction channels. The simulated spectra are compatible with the data for the case of two-pion production via excitation in the target proton of the Roper resonance and its decay to a proton and two pions, as is demonstrated in Fig. 9 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 according to Hirenzaki *et al.* [24] the contributions from the Roper excitation in the α particle and from the double Δ excitations are relatively small in the $p(\alpha, \alpha')p\pi\pi$ reaction, and they may be neglected.

Figure 10 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 $q_{\alpha'}/Z = 3.25$ GeV/c, $q_{\alpha'}/Z = 3.15$ GeV/c, and $q_{\alpha'}/Z = 3.06$ GeV/c. In the simulations, the BW Roper resonance parameters from Refs. [3,29,33] were used. One can see [Fig. 10(a)] that the simulated spectrum of $M(p\pi\pi)$ is in reasonable agreement with the experimental data when the standard Roper parameters (from PDG) are assumed ($M_R =$ 1440 MeV, $\Gamma_R = 350$ MeV [29]). The results of the simulation with the Roper parameters from Ref. [3] ($M_R = 1390$ MeV, $\Gamma_R = 190$ MeV) are in somewhat worse agreement with the data [see Fig. 10(b)]. However, in view of the insufficient precision of the data and because of some uncertainties in the performed analysis, in particular in the contribution of the higher mass $N(1520)D_{13}$ resonance, our data analysis does not allow us to give preference to one of these two considered sets of the Roper parameters. The $M(p\pi\pi)$ distribution simulated with the Roper parameters from Ref. [33] ($M_R = 1485$ MeV, $\Gamma_R = 284$ MeV) is in noticeable disagreement with our data [see Fig. 10(b)]. According to a very recent partial-wave analysis of Sarantsev *et al.* [34], the BW Roper resonance parameters are $M_R = 1436\pm$

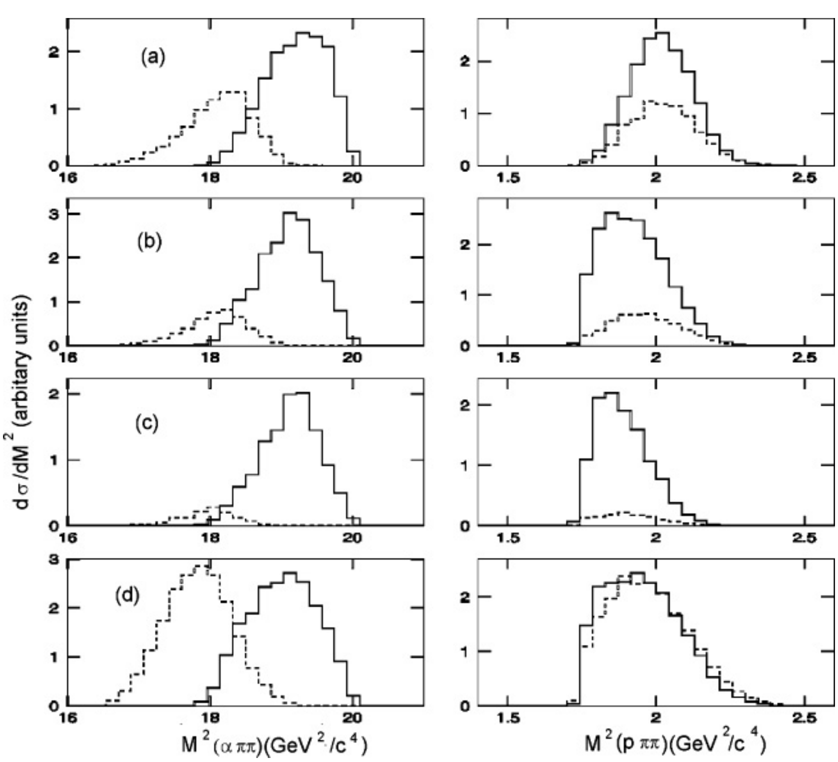

FIG. 8. Monte Carlo simulations of the invariant-mass-squared $M^2(\alpha\pi\pi)$ and $M^2(p\pi\pi)$ distributions for the $p(\alpha, \alpha')p\pi\pi$ reaction. The solid and dashed lines correspond, respectively, to forward and backward emitted protons in the N^* center-of-mass system for the SPES4 momentum setting $q_{\alpha'}/Z = 3.06$ GeV/c. The (a), (b), (c), and (d) parts of the figure correspond to diagrams (a), (b), (c), and (d) in Fig. 7.

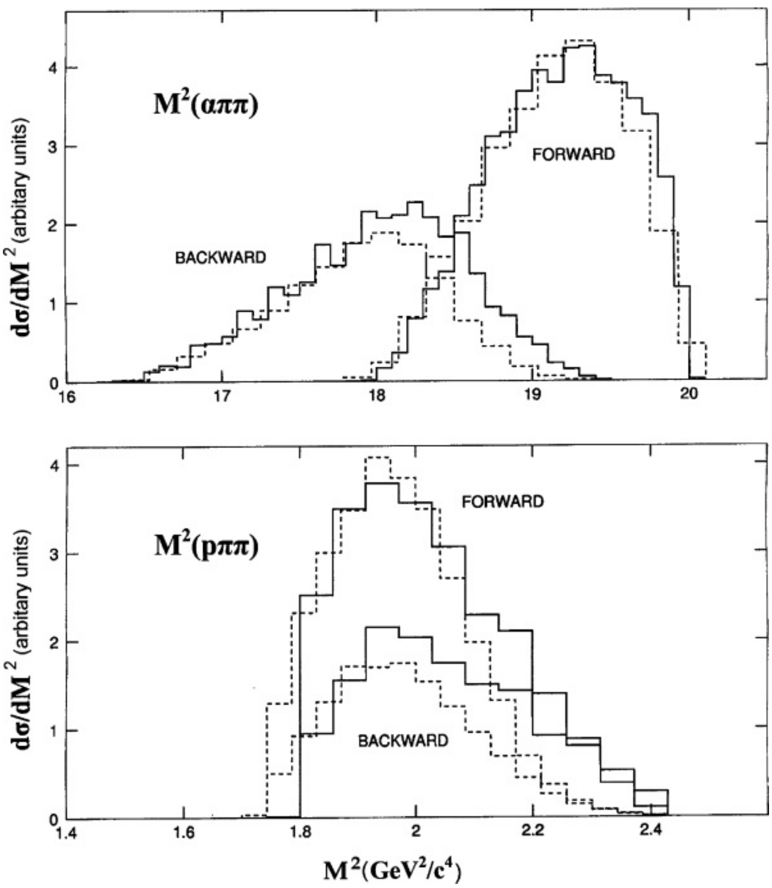

FIG. 9. Comparison of the simulated invariant-mass-squared $M^2(\alpha\pi\pi)$ and $M^2(p\pi\pi)$ distributions (dashed line) with the distribution obtained from the experimental data (solid line) for the $p(\alpha, \alpha')p\pi\pi$ reaction for the forward and backward emitted protons in the N^* center-of-mass system at $q_{\alpha'}/Z = 3.06$ GeV/c. The Monte Carlo simulations are performed by assuming Roper excitation in the target.

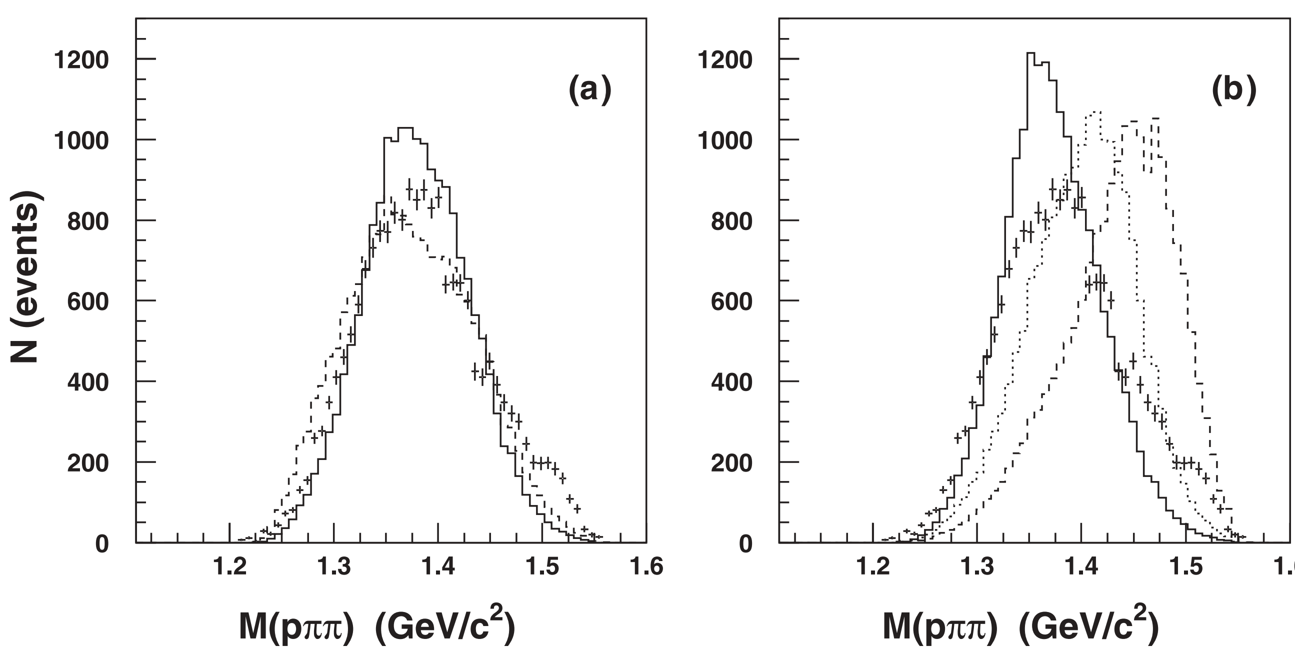

FIG. 10. Comparison of the simulated invariant-mass distributions $M(p\pi\pi)$ (solid, dashed, and dotted lines) with the experimental one (crosses) obtained from the data of the 3.06, 3.15, and 3.25 GeV/c SPES4 momentum settings. (a) The dashed line is for the phase-space calculations and the solid line is for the Roper excitation with $M_R = 1440$ MeV, $\Gamma_R = 350$ MeV [29]. (b) The solid line is for the Roper excitation with $M_R = 1390$ MeV, $\Gamma_R = 190$ MeV [3]; the dotted line is for the Roper excitation with $M_R = 1485$ MeV, $\Gamma_R = 284$ MeV [33]; the dashed line is for the $N(1520)D_{13}$ excitation with $M_D = 1520$ MeV, $\Gamma_D = 120$ MeV [29]. The simulated spectra are normalized to the experimental one.

15 MeV, $\Gamma_R = 335 \pm 40$ MeV. However, the new data of the BES Collaboration on the J/ψ decay [35] and of the CELSIUM-WASA Collaboration on pion production in pp collisions [36] are in favor of smaller values of the Roper mass and width: $M_R \simeq 1360$ MeV, $\Gamma_R \simeq 150$ MeV.

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. 10(b)]. 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 $M(p\pi\pi)$ spectrum 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]. 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 10–20%.

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 a mass of about 1390–1440 MeV), 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 nonresonant two-pion production [see Fig. 10(a)], the difference between the shapes of the $M(p\pi\pi)$ distributions for the nonresonant 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 nonresonant contribution has been made by Alvarez-Ruso *et al.* [37] for the case of inelastic pp scattering at 1 GeV. It was shown that the nonresonant contribution should be about two orders smaller than the resonant one. The same should also be the case for αp scattering. Therefore, the nonresonant 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 $\sim$1 GeV/nucleon) proceeds mainly through the intermediate state, which is the Roper resonance excited in the target proton. Because of 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 [26,27], which is a coupled pion pair in the isospin $I = 0$, S-wave state [Fig. 2(c)].

B. Intermediate-state decay

In πN scattering (see Ref. [29]), 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, $N^* \to N(\pi\pi)^{I=0}_{\text{Swave}}$, 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 and co-workers [17,18] performing a partial-wave analysis of the $\pi N \to N\pi$ and $\pi N \to N\pi\pi$ scattering data introduced a σ meson (or ε in the notation of Ref. [38]) as an S-wave isoscalar $\pi\pi$ interaction. In the literature [26,27], it was discussed whether this σ state is in fact a genuine meson or just some effective meson simulated by the reaction dynamics effects. Not long ago, Hernández *et al.* [38] showed that the shapes of the spectra of the invariant πN and $\pi\pi$ masses of the decay products of the Roper resonance, such as those discussed by Manley and co-workers [17,18], may be explained by the processes of the intermediate-state Δ production and the pions final-state interaction, which can simulate an effective σ meson. 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. 11). As follows from theory [38], 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 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 Ref. [29], a sequential Δ decay [Fig. 11(a)] is dominant. However, 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. 11(b)] is expected.

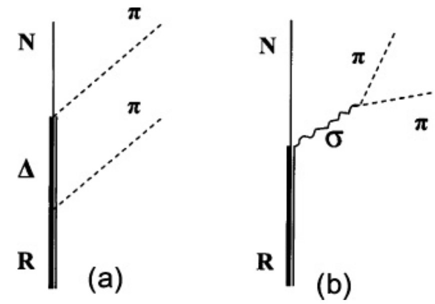

FIG. 11. Diagrams for the Roper resonance decay with emission of two pions in Manley's approach according to Ref. [38]. (a) Decay through the intermediate Δ state, $N^* \to \Delta\pi \to N\pi\pi$. (b) Decay through the intermediate σ-meson state, $N^* \to N\sigma \to N\pi\pi$.

In Figure 12, 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 $M^2(\pi\pi)$ spectra are obtained from the missing-mass-squared, M^2_{miss}, spectra shown in Fig. 6 by subtracting the $M^2(\pi)$ contributions of the one-pion-production channels, the $M^2(\pi)$ spectra being parametrized by Gaussians (see dashed curves in Fig. 6). 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: $M_\Delta = 1232$ MeV, $\Gamma_\Delta = 120$ MeV [29] and $M_\sigma =$ 600 MeV, $\Gamma_\sigma = 600$ MeV [26]. 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

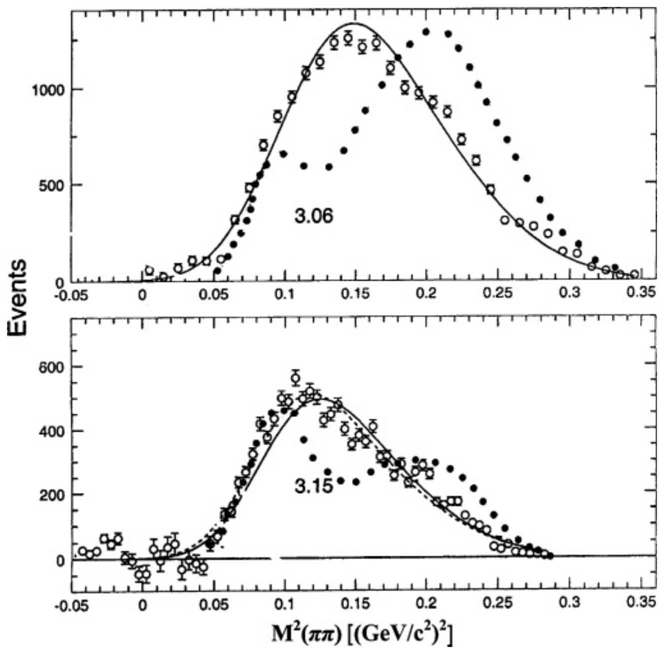

FIG. 12. Invariant-mass-squared $M^2(\pi\pi)$ distributions for the $p(\alpha, \alpha')p\pi\pi$ reaction. Open points show experimental data. Solid curves are the results of the Monte Carlo simulations made by assuming the $N^* \to p\sigma \to p\pi\pi$ decay. Dotted curves are the results of the Monte Carlo simulations made by assuming the $N^* \to \Delta\pi \to p\pi\pi$ decay. The dashed line in the lower plot is the result of the Monte Carlo simulation made by 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.

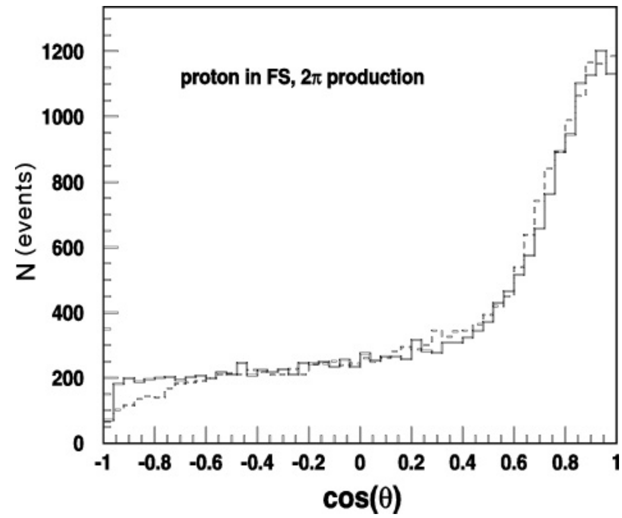

FIG. 13. Angular distribution of the emitted protons in the N^* center-of-mass system, not corrected for the SPES4-π acceptance. Angle θ is the angle between the proton momentum and the momentum transfer $\mathbf{q}_\alpha - \mathbf{q}_{\alpha'}$ in the rest frame of N^*. The solid line shows the experimental data; the dashed line is the normalized Monte Carlo calculation, made by assuming isotropic N^* decay. (The simulated spectrum, as well as the experimental one, is distorted by the SPES4-π acceptance.)

the simulated spectra owing to the large value of Γ_σ. 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 Ref. [38]):

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

where $\mathbf{q}_{\pi_1}$ and $\mathbf{q}_{\pi_2}$ are the pion momenta in the N^* center-of-mass system. We have not included small spin-dependent terms in Eq. (1). According to Refs. [15,16], the contribution of the spin-dependent terms is about 1/16 that of the $\mathbf{q}_{\pi_1} \cdot \mathbf{q}_{\pi_2}$ term, and to a good approximation it can be neglected. As a result of the factor $A(\mathbf{q}_{\pi_1}, \mathbf{q}_{\pi_2})$, 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 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^* center-of-mass system with similar momenta in the same direction; the second peak corresponds to the events when the pions are emitted in opposite directions.

As one can see in Fig. 12, 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 $M^2(\pi\pi)$ determined by 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 resonance excited in the $p(\alpha, \alpha')p\pi\pi$ reaction at an energy of ∼1 GeV/nucleon decays mainly as $N^* \to p\sigma \to p\pi\pi$.

This conclusion is also supported by the extracted angular distribution of the emitted protons in the N^* center-of-mass system. The obtained distribution agrees with the isotropic decay of N^* (see Fig. 13), and therefore it agrees with the assumed picture of decay of the Roper resonance (with spin 1/2) to a nucleon and a scalar meson.

Our conclusion that the Roper resonance excited in αp scattering decays predominantly through the $N^* \to p\sigma \to p\pi\pi$ channel is very different from previous πN-scattering-analyses results [29]. However, our result nicely correlates with recent investigations of the two-pion production in pp inelastic-scattering experiments at energies of 0.650–0.775 GeV [14–16,39]. 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. Glozman and Riska [40] also find at variance with PDG [29] that the σN channel of the Roper resonance decay is more important than the $\pi\Delta$ channel. A similar statement was made as well by Krehl *et al.* [7].

It is worth pointing out that in a recent paper of the Crystal Ball Collaboration [41], Prakhov *et al.*, analyzing Dalitz

[1] Better agreement with the data can be achieved in this case (see Fig. 12) 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.

plots of the reaction $\pi^- p \rightarrow \pi^0\pi^0 n$ from threshold to $q_\pi = 750$ MeV/c, have come to the conclusion that the Roper resonance excited in the studied reaction decays predominantly through the intermediate Δ resonance, the channel of the Roper decay through the σ meson being of minor importance. However, as the authors of this paper believe, a better understanding of the role and contribution of the σ meson in two-pion production can be achieved by the use of a detailed partial-wave analysis of the data. Sarantsev *et al.* [34], who performed a combined partial-wave analysis of several pion-production reactions including the aforementioned data [41], conclude, in contrast to Ref. [41], that the channel of the Roper decay through the σ meson is rather important, with the contribution of this channel being about three times larger than that given by PDG [29]. As 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.

IV. CONCLUSIONS

The two-pion-production $p(\alpha, \alpha')p\pi\pi$ reaction has been studied in a semiexclusive 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 proton. The results of the measurements are qualitatively compared with the simulated invariant-mass spectra based on the predictions of the Oset-Hernandez model using Manley's approach to the Roper decay. The invariant-mass distributions $M(\alpha'\pi\pi)$, $M(p\pi\pi)$, and $M(\pi\pi)$ are obtained and analyzed. The results are compatible with the assumption that the studied $p(\alpha, \alpha')p\pi\pi$ reaction proceeds via scalar excitation in the target proton of the Roper resonance as an intermediate state, which decays predominantly through the $N^* \rightarrow p\sigma \rightarrow p\pi\pi$ channel. The obtained results are in favor 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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