TWO-PION PRODUCTION IN αp SCATTERING AT 1 GeV/NUCLEON IN THE ENERGY REGION OF THE $P_{11}(1440)$ RESONANCE EXCITATION

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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 to the problem of the $P_{11}(1440)$ (Roper) resonance. This reaction was investigated in an inclusive experiment 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 $P_{11}(1440)$ resonance was discovered. Two peaks were observed in the reaction cross section *vs* the missing energy $\omega = E_{\alpha'} - E_\alpha$ distribution (see Fig. 1). A large one, in the region of small energy transfers $\omega \simeq -0.25$ GeV, was evidently due to the $P_{33}(1232)$ (Δ) resonance excitation in the α-particle, and a smaller one, in the region of $\omega \simeq -0.55$ GeV, was interpreted as a signal of the $P_{11}(1440)$ resonance excitation in the target proton. This interpretation was confirmed later by more detailed theoretical considerations. According to theory, only three diagrams (see Fig. 2) dominate in αp inelastic scattering at this energy. The first diagram (*a* in Fig. 2) corresponds to excitation of the Δ resonance in the α-particle projectile, while the second and third diagrams (*b* and *c* in Fig. 2) correspond to excitation of the Roper resonance in the target proton mainly through an exchange of a neutral isoscalar "sigma meson" between the α-particle and the proton. The contribution of all other possible diagrams is practically negligible.

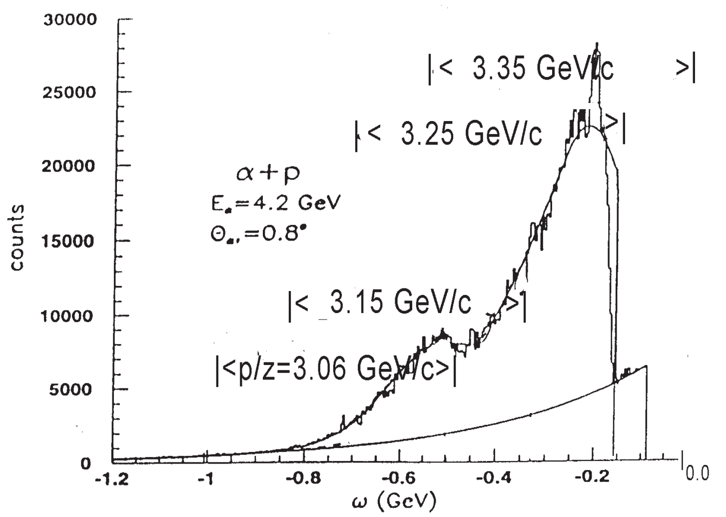

Fig. 1. Inclusive missing energy spectrum of inelastic αp scattering. The acceptance boundaries of the four different $q_{\alpha'}/Z$ momentum settings of the present SPES4-π experiment are marked

Note that due to the isoscalar nature of α-particles and isospin conservation, a direct excitation of the Δ resonance in the proton is forbidden. The decay products from the $p(\alpha, \alpha')X$ reaction may be either a nucleon (proton or neutron) and one pion resulting from the decay of the Δ or Roper resonances (diagrams *a* and *b* in Fig. 2), or a nucleon and two pions resulting from the decay of the Roper resonance (diagram *c* in Fig. 2).

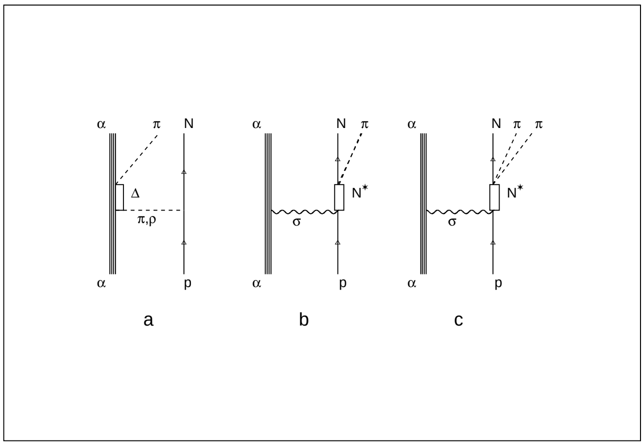

Fig. 2. Main diagrams contributing to the $p(\alpha,\alpha')X$ reaction: (a) Δ excitation in the projectile, (b) N^* excitation in the target with the following one-pion ($N\pi$) decay, and (c) N^* excitation in the target with the following two-pion ($N\pi\pi$) decay

The Roper resonance is the lowest positive parity excited state N^* of the nucleon and is in many respects a very intriguing and important object. This resonance is important in many intermediate-energy processes and also may play a significant role in the three-body nuclear forces and in the swelling of nucleons in nuclei. The result of the inclusive $p(\alpha,\alpha')X$ experiment was interpreted as an observation of the scalar excitation of the $P_{11}(1440)$ resonance which is a breathing mode monopole ($L=0$) excitation of the nucleon. In this interpretation, the $P_{11}(1440)$ resonance mass can be related to the compressibility of the nuclear matter (on the nucleonic level). Some authors have also supposed that the Roper resonance is in fact a superposition of two structures, one being understood as the nucleon breathing mode and the other as double excitation of the Δ resonance. The first structure 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.

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, as it has already been mentioned, 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 higher baryon resonances should be expected small. A deficiency of the inclusive αp experiment 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 resonance excited in the αp-scattering reaction, an exclusive (or semi-exclusive) experiment at the Saturne II accelerator (Saclay) has been performed. Here, we present the results of this experiment in respect to the two-pion production reaction $p(\alpha,\alpha')p\pi\pi$.

Note that the channel of one-pion decay of the Roper resonance strongly interferes with the channel of decay of the Δ resonance, the latter decaying in practically pure one-pion decay mode. This interference makes the separation of the channel of one-pion decay of the Roper resonance from the channel of decay of the Δ resonance to be a complicated task. As for the channel of two-pion decay of the Roper resonance, the contribution of other possible two-pion production channels and interference with them are expected to be small and this allows one to extract much less ambiguous results.

2. Experiment and data analysis

The experimental study of the $p(\alpha,\alpha')pX$ reaction discussed in the present paper was carried out at the Saturne-II accelerator (CE Saclay, France) at a beam of α-particles with a momentum of q_α= 7 GeV/c (E_α=4.2 GeV) [1]. The scattered α-particles and the charged reaction products (p, π^+ or π^-) were registered with the SPES4-π setup (Fig. 3). The installation [2, 3] included the high resolution magnetic spectrometer SPES4, which was used in earlier experiments, and a wide-aperture non-focusing Forward Spectrometer (FS). FS consisted of an analyzing large-gap dipole magnet TETHYS, a drift chamber telescope and a hodoscope of scintillation counters. A liquid hydrogen target, 60 mm in length, was located inside the TETHYS magnet.

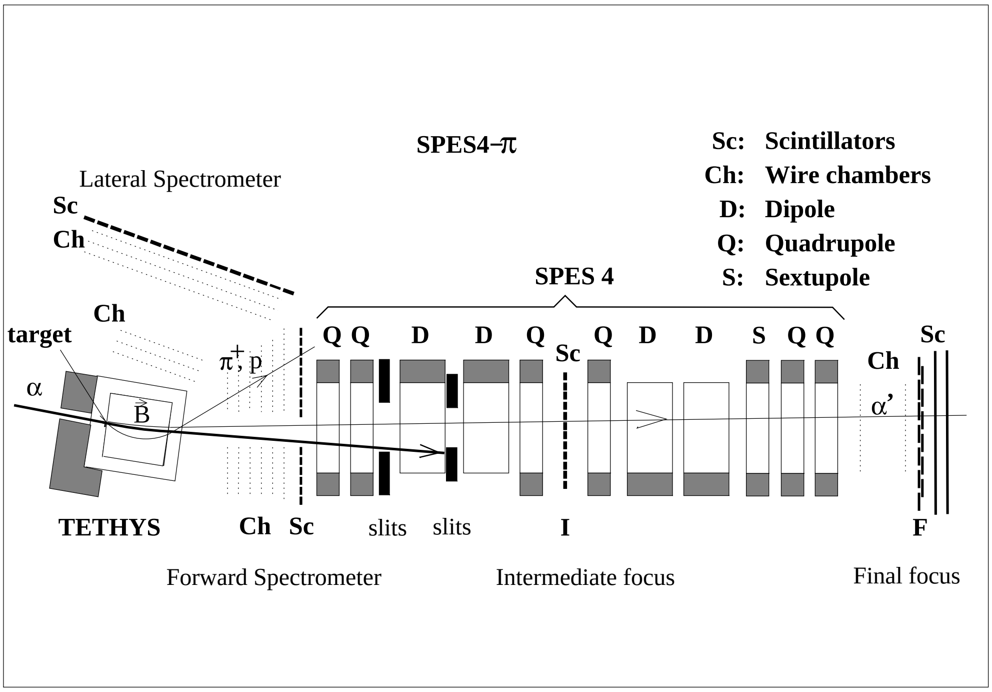

Fig. 3. Schematic view of the SPES4-π setup. TETHYS – large-gap dipole magnet; D,Q,S – magnetic elements of the SPES4 spectrometer; Ch – wire chambers; Sc – hodoscope of scintillation counters

The measurements were 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 to allow the study of the reaction at the values of the energy transfer ω from –0.15 GeV to –0.9 GeV. The ω-intervals accepted at different momentum settings of SPES4 are indicated in Fig. 1. In this paper, the data obtained by detecting the scattered α-particles with SPES4 and only protons with FS are discussed. The measured momenta $\mathbf{q}_{\alpha'}$ and $\mathbf{q}_p$ of the scattered α-particle and secondary proton allowed us to determine the missing mass[1] $M_{\rm miss}$ and the invariant masses $M(p\pi\pi)$ and $M(\alpha'\pi\pi)$.

2.1. Intermediate state excitation

Two-pion events were separated from one-pion events in the analysis of the experimental data by making use of the determined values of the squared missing mass $M^2_{\rm miss}$. Figure 4 shows the distributions of $M^2_{\rm miss}$ for the four momentum settings of SPES4. The spectra include the sum of the events from the one-pion and two-pion production channels.

[1]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, 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 that the number of pions is more than two in this reaction at the considered energy is expected to be very small.

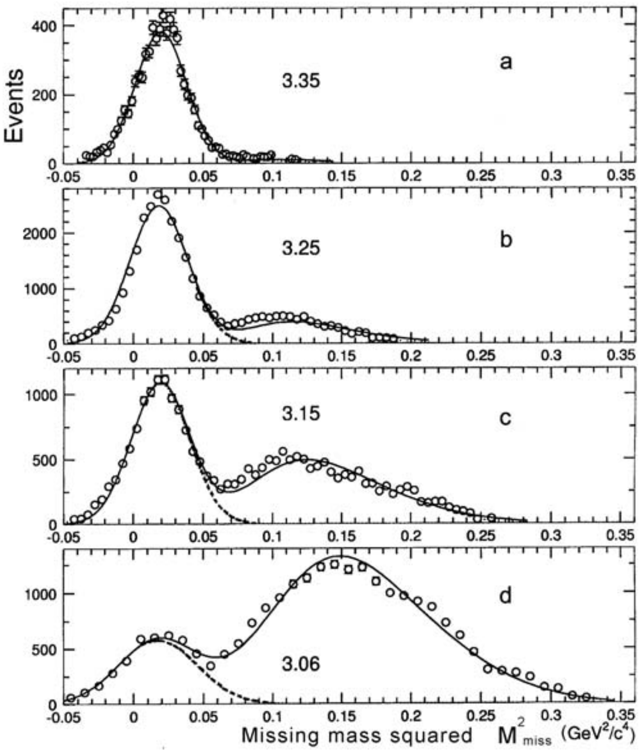

Fig. 4. Missing mass squared spectra $M^2_{\rm miss}$ for the $p(\alpha,\alpha')pX$ reaction for different SPES4 momentum settings. The open points are the experimental data. The solid lines are the sums of the one-pion production distributions, parametrized by Gaussians (dotted lines), and the two-pion production distributions, calculated taking into account the $p(\alpha,\alpha')p\pi\pi$ phase space, α-particle form factor and SPES4-π acceptance

It is seen (Fig. 4a) 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 (that is at $M_{\rm miss}\simeq$0.14 GeV/c^2) dominates in the spectrum. Evidently, this peak is due to one-pion events production mostly from 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_{\rm miss}\simeq$0.02 (GeV/c^2)^2 reflects the resolution of the reconstructed values of $M^2_{\rm miss}$. This resolution was practically identical for all SPES4 settings. For the SPES4 momentum setting $q_{\alpha'}$/Z=3.25 GeV/c, the contribution from two-pion events (at $M^2_{\rm miss}\geq$0.09 (GeV/c^2)^2) is more prominent (Fig. 4b). In the interval of 0.04 (GeV/c^2)$^2\leq M^2_{\rm miss}\leq$ 0.09 (GeV/c^2)^2, the one-pion and two-pion events are not resolved. As for the settings $q_{\alpha'}$/Z=3.15 GeV/c and $q_{\alpha'}$/Z=3.06 GeV/c, the data show (Figs. 4c,d) that the two-pion production is an important channel of the $p(\alpha,\alpha')pX$ reaction at the energy 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 registration of two-pion events in our experiment is higher than that for registration of one-pion events, since the protons to be registered by FS are emitted in the forward direction in a more narrow angular cone in the first case in comparison with the second one. Note also that the registered one-pion events are from the reaction $p(\alpha,\alpha')p\pi^0$, while 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 being not separated in this study.

We can suppose that the detected two-pion events are due to the 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 simulated spectra are compatible with the data, as it is demonstrated in Fig. 5, for the assumed channel of the two-pion production *via* excitation in the target proton of the $P_{11}(1440)$ resonance and its decay to a proton and two pions.

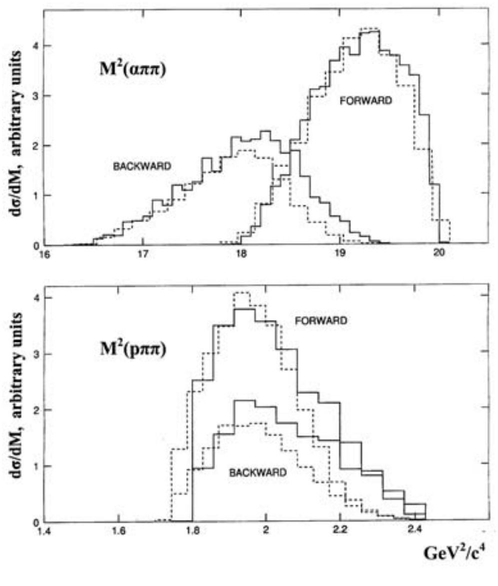

Fig. 5. Invariant mass squared $M^2(\alpha'\pi\pi)$ and $M^2(p\pi\pi)$ distributions of the reaction $p(\alpha,\alpha')p\pi\pi$ for forward and backward emitted protons in the N^* center-of-mass system at p/Z=3.06 GeV/c. Solid line – experimental data; dashed line – Monte Carlo (MC) simulation for the case of N^* excitation in the target

In Fig. 5, a comparison of the simulated spectra with the experimental data is presented for the SPES4 momentum setting $q_{\alpha'}$/Z=3.06 GeV/c. Similar results are also obtained for the setting $q_{\alpha'}$/Z=3.15 GeV/c. Note that the theoretical considerations predict that the contributions from the Roper excitation in the α-particle and from the double excitation of the Δ resonance are relatively small in the $p(\alpha,\alpha')p\pi\pi$ reaction and they may be neglected.

Fig. 6 presents a comparison of the simulated spectra for 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 $P_{11}(1440)$ resonance parameters from different analyses were assumed. One can see (Fig. 6a) that the simulated spectrum of $M(p\pi\pi)$ is in reasonable agreement with the experimental data when the standard parameters (M_R = 1440 MeV, Γ_R = 359 MeV) of the Roper resonance are assumed[2]. We have also performed a simulation under an assumption that two-pion events are produced *via* excitation and decay of the higher mass $D_{13}(1520)$ baryon resonance. In this case, the results of the simulations are in drastic disagreement with the data (Fig. 6b). At the same time, it is seen that a small admixture of events from the D_{13} resonance in the experimental spectrum of $M(p\pi\pi)$ is possible. Adding to the simulated spectrum a small contribution of events from the decay of the 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).

Thus, we see that our data are consistent with the scenario that two-pion events are produced mostly *via* the excitation of the Roper resonance in the target proton with its following decay into a proton and two pions. It should, however, be admitted that the shape of the simulated $M(p\pi\pi)$ spectrum is practically also consistent with the data for the case of non-resonant two-pion production (see Fig. 6a). This may be explained by the fact that the width of the Roper resonance is large and the Roper resonance propagator exerts very little influence on the shape of the simulated $M(p\pi\pi)$ spectrum. An estimate of the non-resonant contribution has been made by the Valencia University theory group for the case of *pp* inelastic scattering at 1 GeV. It has been 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

[2]Due to insufficient precision of the experimental data obtained and in view of an uncertainty in the contribution of events from the decay of the $D_{13}(1520)$ resonance, we cannot exclude a possibility that the Roper resonance has other parameters, a slightly smaller mass and a smaller width.

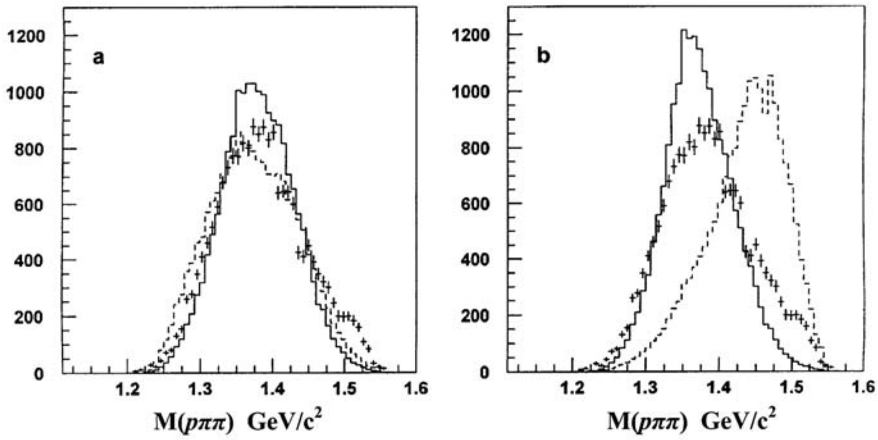

Fig. 6. Experimental and simulated invariant mass distributions for $M(p\pi\pi)$. Experimental data are shown by crosses. a) Dotted line – phase space calculations; solid line – excitation of the Roper resonance with $M = 1440$ MeV, $\Gamma = 350$ MeV (from PDG). b) Solid line – excitation of the P_{11} resonance with $M = 1390$ MeV, $\Gamma = 190$ MeV (from H.P. Morsch and P. Zupranski, Phys. Rev. C **61**, 024002 (1999)), dotted line – excitation of the D_{13} resonance with $M = 1520$ MeV, $\Gamma = 120$ MeV. The α-particle form factor and the spectrometer acceptance are included. The data from all momentum settings are combined. The simulated spectra are normalized to the experimental one

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 $P_{11}(1440)$ resonance excited in the target proton. Due to the isoscalar nature of α-particles, the Roper resonance, as it 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).

2.2. Intermediate state decay

In πN scattering, according to Particle Data Group, the two-pion decay of the Roper resonance occurs mainly either as a simultaneous emission of two pions in the I=0 isospin, S-wave state, $N^* \rightarrow N(\pi\pi)^{I=0}_{S-wave}$ or as a sequential decay through the Δ resonance, $N^* \rightarrow \Delta\pi \rightarrow N\pi\pi$, with branching ratios of ~10% and ~30%, respectively. The σ (or ϵ in different notation) meson was introduced as a S-wave isoscalar $\pi\pi$ interaction in a partial-wave analysis of the $\pi N \rightarrow N\pi$ and $\pi N \rightarrow N\pi\pi$ scattering data. It was discussed whether this σ state is in fact a genuine meson or just some effective meson simulated by the reaction dynamics effects. In the present analysis, we consider two possible channels of the Roper resonance two-pion decay, namely, through the Δ resonance and through the real (or effective) σ meson (Fig. 7).

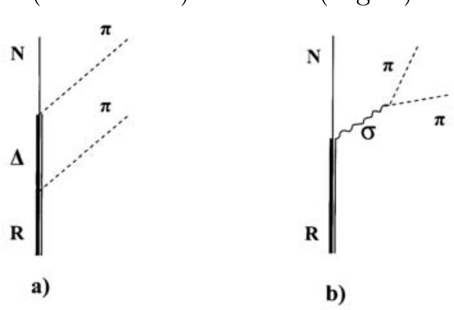

Fig. 7. Diagrams for the Roper resonance decay into two pions: a) sequential decay through Δ: $N^* \rightarrow \Delta\pi \rightarrow N\pi\pi$; b) decay through the $\sigma(\epsilon)$ meson: $N^* \rightarrow N\sigma(\epsilon)$

As follows from theory, the shapes of the spectra of the invariant mass $M(\pi\pi)$ of the pions emitted in the Roper resonance decay are essentially different for these two-pion production channels (Fig. 7). Therefore, a comparison of our experimental data with theoretical predictions can be used to find out what process is more important for the decay of the Roper resonance excited in inelastic αp scattering. In πN scattering, the sequential decay of the Δ resonance (Fig. 7a) is dominant. This should be the same in αp scattering if the same resonance is excited in both reactions. On the other hand, according to the two-resonance picture, the breathing mode of the nucleon is strongly excited in αp scattering, and a different decay pattern (shown in Fig. 7b) is expected.

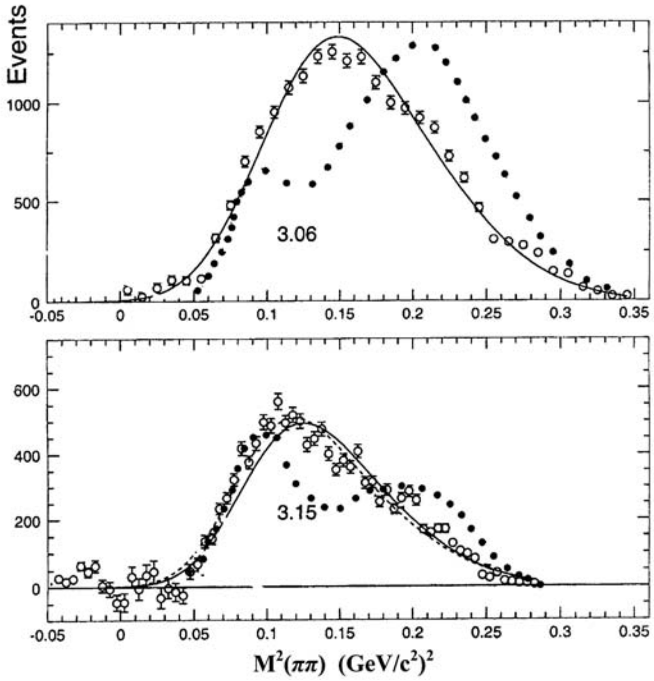

Fig. 8. Invariant mass squared $M^2(\pi\pi)$ distribution for the two-pion production channel in the $p(\alpha,\alpha')p\pi\pi$ reaction. Open points – experimental data. Solid lines – the results of the MC phase space simulations assuming $N^* \to p\sigma \to p\pi\pi$ decay. Dotted curves – the results of the MC simulations assuming $N^* \to \Delta\pi \to p\pi\pi$ decay. Dashed line in the lower plot – the result of the MC simulation assuming the decay through the σ meson with a small admixture of the decay through the Δ resonance

In Fig. 8, 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 the events of the two-pion production channel of the $p(\alpha,\alpha')pX$ reaction. The experimental spectra $M^2(\pi\pi)$ are obtained from the missing mass squared $M^2_{\rm miss}$ spectra shown in Fig. 4 by subtracting the one-pion production contributions $M^2(\pi)$, which are parametrized by Gaussians (see dotted curves in Fig. 4). In the presented simulation, the σ meson and Δ resonance are described by the Breit-Wigner distributions. The α-particle form factor and the SPES4-π acceptance are also taken into account. Furthermore, the simulated spectra are smeared to take into account the experimental resolution of $M^2(\pi\pi)$, which is estimated from the width of the $M^2(\pi)$ spectra (see Fig. 4). The following parameters for the Δ resonance and σ meson are used: M_Δ = 1232 MeV, Γ_Δ = 120 MeV, and M_σ = 600 MeV, Γ_σ = 600 MeV. It should be noted, however, that due to the large width Γ_σ of the σ meson the specific parameters of the σ meson exert practically no influence on the simulated spectra. As for the channel of the decay through the intermediate Δ-resonance state, the amplitude of this process is strongly influenced by the following kinematical factor [3]

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

where $\mathbf{q}_{\pi_1}$ and $\mathbf{q}_{\pi_2}$ are the pion momenta in the N^* center-of-mass system. As a result of this factor influence, the simulated spectra of $M^2(\pi\pi)$ have two maxima, at small values of $M(\pi\pi)$ (at $M(\pi\pi)$ close to 0.3 GeV/c^2) and at large values of $M(\pi\pi)$. The first peak corresponds to the events when

[3] We have neglected small spin terms in Eq. (1).

both emitted pions fly in the N^* center-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.

As one can see in Fig. 8, 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. Differently, the shape of the simulated spectrum $M^2(\pi\pi)$ assuming the Roper resonance 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[4]. Thus, the $M^2(\pi\pi)$ spectra measured in this experiment suggest that the $P_{11}(1440)$ resonance excited in the $p(\alpha,\alpha')pX$ reaction at an energy of ~1 GeV/nucleon decays mainly as $N^* \to p\sigma \to p\pi\pi$.

This result is also supported by the extracted angular distribution of the emitted protons in the N^* center-of-mass system. This distribution is close to isotropic (see Fig. 9) and therefore agrees with the assumed picture of the decay of the Roper resonance (with the spin 1/2) to a nucleon and a scalar meson.

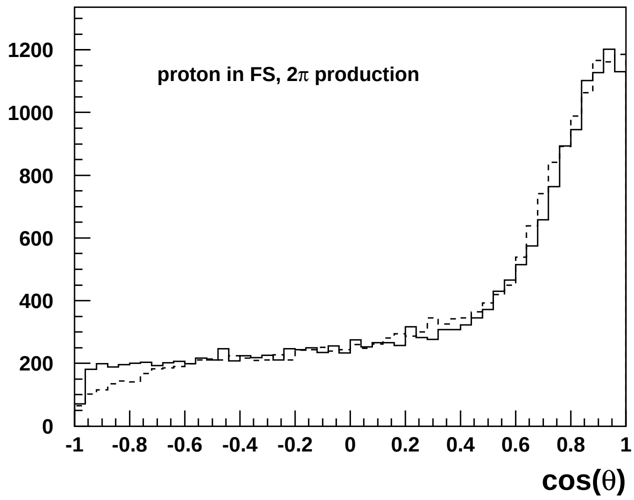

Fig. 9. Angular distribution of the protons in the N^* center-of-mass system (not corrected for the SPES4-π acceptance). θ is the angle between the proton and the momentum transfer $\mathbf{q}_\alpha - \mathbf{q}_{\alpha'}$ in the rest frame of N^*. Solid line – experimental data, dashed line – normalized MC calculation assuming isotropic N^* decay. The data from settings 3.06, 3.15 and 3.25 GeV/c are included

Our conclusion that the $P_{11}(1440)$ resonance excited in αp scattering decays predominantly through the $N^* \to p\sigma \to p\pi\pi$ channel is very different from the πN scattering result. On the other hand, our result nicely correlates with recent investigations of the two-pion production in pp inelastic scattering experiments at energies of 0.650–0.775 GeV (J. Petzold *et al.*, Phys. Rev. C **67**, 052202R (2003)). The authors of these studies come to the conclusion that the two-pion production in pp scattering at these energies proceeds mainly through the excitation of the Roper resonance which decays predominantly through the intermediate σ meson. Note that in a recent analysis of the $\pi N \to N\pi\pi$ data it has been also found by L.Ya. Glozman and D.O. Riska (Phys. Rep. **268**, 263 (1996)) – in contrast to the earlier $\pi N \to N\pi\pi$ analyses conclusion – that the σN channel is more important than the $\pi\Delta$ channel.

3. Conclusion

The two-pion production in the inelastic $p(\alpha,\alpha')p\pi\pi$ reaction was studied in a semi-exclusive experiment at the Saturne-II accelerator (Saclay) at an energy of ≃1 GeV/nucleon with the registration of the scattered α-particle and the secondary proton. The invariant mass distributions $M(\alpha'\pi\pi)$, $M(p\pi\pi)$ and $M(\pi\pi)$ were 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

[4]Better agreement with the data can be achieved in this case (see Fig. 8) if a small admixture of events corresponding to the Roper resonance decay through the intermediate state of the Δ resonance is added to the simulated spectrum.

resonance as an intermediate state which decays predominantly through the $N^* \to p\sigma \to p\pi\pi$ 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 excitation mode of the nucleon.

This work has been performed by the SPES4-π collaboration. The PNPI participants are: G.D. Alkhazov, A.V. Kravtsov †, V.A. Mylnikov, E.M. Orischin, A.N. Prokofiev, B.V. Razmyslovich, I.B. Smirnov, I.I. Tkach †, S.S. Volkov, A.A. Zhdanov.

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