PROCEEDINGS OF SCIENCE

New data on the quasi-free $np \to np\pi^+\pi^-$ and $np \to pp\pi^-\pi^0$ reactions at 1.25 GeV with HADES

A.K. Kurilkin* **for the HADES collaboration**
Joint Institute of Nuclear Research, 141980 Dubna, Russia
E-mail: akurilkin@jinr.ru

J. Adamczewski-Musch[4], O. Arnold[10,9], E.T. Atomssa[15], C. Behnke[8], J.C. Berger-Chen[10,9], J. Biernat[3], A. Blanco[2], C. Blume[8], M. Böhmer[10], P. Bordalo[2], S. Chernenko[7], C. Deveaux[11], A. Dybczak[3], E. Epple[10,9], L. Fabbietti[10,9], O. Fateev[7], P. Fonte[2,a], C. Franco[2], J. Friese[10], I. Fröhlich[8], T. Galatyuk[5,b], J. A. Garzón[17], K. Gill[8], M. Golubeva[12], F. Guber[12], M. Gumberidze[5,b], S. Harabasz[5,3], T. Hennino[15], S. Hlavac[1], C. Höhne[11], R. Holzmann[4], A. Ierusalimov[7], A. Ivashkin[12], M. Jurkovic[10], B. Kämpfer[6,c], T. Karavicheva[12], K. Kardan[8], I. Koenig[4], W. Koenig[4], B. W. Kolb[4], G. Korcyl[3], G. Kornakov[5], R. Kotte[6], A. Krása[16], E. Krebs[8], H. Kuc[3,15], A. Kugler[16], T. Kunz[10], A. Kurepin[12], A. Kurilkin[7], P. Kurilkin[7], V. Ladygin[7], R. Lalik[10,9], K. Lapidus[10,9], A. Lebedev[13], L. Lopes[2], M. Lorenz[8], T. Mahmoud[11], L. Maier[10], A. Mangiarotti[2], J. Markert[8], V. Metag[11], J. Michel[8], C. Müntz[8], R. Münzer[10,9], L. Naumann[6], M. Palka[3], Y. Parpottas[14,d], V. Pechenov[4], O. Pechenova[8], V. Petousis[14], J. Pietraszko[4], W. Przygoda[3], B. Ramstein[15], L. Rehnisch[8], A. Reshetin[12], A. Rost[5] A. Rustamov[8], A. Sadovsky[12], P. Salabura[3], T. Scheib[8], K. Schmidt-Sommerfeld[10], H. Schuldes[8], P. Sellheim[8], J. Siebenson[10], L. Silva[2], Yu.G. Sobolev[16], S. Spataro[e], H. Ströbele[8], J. Stroth[8,4], P. Strzempek[3], C. Sturm[4], O. Svoboda[16], A. Tarantola[8], K. Teilab[8], P. Tlusty[16], M. Traxler[4], H. Tsertos[14], T. Vasiliev[7], V. Wagner[16], C. Wendisch[6,c], J. Wirth[10,9], J. Wüstenfeld[6], Y. Zanevsky[7] and P. Zumbruch[4]
(HADES collaboration)

[1] Institute of Physics, Slovak Academy of Sciences, 84228 Bratislava, Slovakia
[2] LIP-Laboratório de Instrumentação e Física Experimental de Partículas, 3004-516, Coimbra, Portugal
[3] Smoluchowski Institute of Physics, Jagiellonian University of Cracow, 30-059 Kraków, Poland
[4] GSI Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt, Germany
[5] Technische Universität Darmstadt, 64289 Darmstadt, Germany
[6] Institut für Strahlenphysik, Helmholtz-Zentrum Dresden-Rossendorf, 01314 Dresden, Germany
[7] Joint Institute of Nuclear Research, 141980 Dubna, Russia
[8] Institut für Kernphysik, Goethe-Universität, 60438 Frankfurt, Germany
[9] Excellence Cluster 'Origin and Structure of the Universe' , 85748 Garching, Germany
[10] Physik Department E12, Technische Universität München, 85748 Garching, Germany
[11] II.Physikalisches Institut, Justus Liebig Universität Giessen, 35392 Giessen, Germany
[12] Institute for Nuclear Research, Russian Academy of Science, 117312 Moscow, Russia
[13] Institute of Theoretical and Experimental Physics, 117218 Moscow, Russia
[14] Department of Physics, University of Cyprus, 1678 Nicosia, Cyprus
[15] Institut de Physique Nucléaire (UMR 8608), CNRS/IN2P3 - Université Paris Sud, F-91406 Orsay Cedex, France
[16] Nuclear Physics Institute, Academy of Sciences of Czech Republic, 25068 Rez, Czech Republic
[17] LabCAF. Dpto. Física de Partículas, Univ. de Santiago de Compostela, 15706 Santiago de Compostela, Spain
[a] Also at ISEC Coimbra, Coimbra, Portugal
[b] Also at ExtreMe Matter Institute EMMI, 64291 Darmstadt, Germany
[c] Also at Technische Universität Dresden, 01062 Dresden, Germany
[d] Also at Frederick University, 1036 Nicosia, Cyprus
[e] Also at Dipartimento di Fisica Generale and INFN, Università di Torino, 10125 Torino, Italy

The results on double-pion production in tagged quasi-free np collisions at a deutron incident beam energy of 1.25 GeV/c measured with the High-Acceptance Di-Electron Spectrometer (HADES) installed at GSI are presented. The specific acceptance of HADES allowed for the first time to obtain high-precision data on $\pi^+\pi^-$ and $\pi^-\pi^0$ production in np collisions in a region corresponding to large transverse momenta of the secondary particles. The obtained differential cross section data provide strong constraints on the production mechanisms and on the various baryon resonance contributions ($\Delta\Delta$, $N(1440)$, $N(1520)$, $\Delta(1600)$). The invariant mass and angular distributions from the $np \to np\pi^+\pi^-$ and $np \to pp\pi^-\pi^0$ reactions are compared with different theoretical model predictions.

XXII International Baldin Seminar on High Energy Physics Problems,
15-20 September 2014
JINR, Dubna, Russia

*Speaker.

1. Introduction

Double-pion production in nucleon-nucleon (NN) collisions presents the particular interest in view of studying of the baryon excitation spectrum and the baryon-baryon interaction properties. At present time the $\pi\pi$ production are considered as a key process towards a better understanding of hadronic interactions, because baryon excitation processes contribute significantly to meson and dilepton production. In comparison with πN and γN interactions where the excitation of a resonance decaying into two pions can also be studied, the NN reactions allow to investigate the simultaneous excitation of two baryons. Two-pion production mode presents a different selectivity with respect to the various resonances. In particular, with the two pions in the isospin 1 channel, the excitation of baryonic resonances coupled to the ρ meson can be studied. It is of high interest for a better understanding of the dilepton production in nucleon-nucleon reactions and also in nucleon matter due to the expected modifications of the ρ meson spectral functions [1]. Finally, the comparison of two-pion production in pp and np channels could shed some light on the origin of the very large isospin dependence of the dilepton emission observed by the HADES experiment [2]. A number of low statistic experiments on pion productions in NN interactions have been performed in the past spanning the energy region from threshold to many GeV's by using bubble chamber techniques [3]-[4]. Recently, double-pion production in NN collisions has been accurately measured at CELSIUS [5, 6, 7], COSY [8, 9], KEK [10], and PNPI-Gatchina [11] facilities. The intriguing results, obtained by the WASA collaboration [8, 9, 12, 13, 14, 15, 16, 17, 18] renewed the interest for the study of the two-pion production in NN collisions, in order to check the possible contribution of a dibaryon resonance [19, 20]. As results of many theoretical efforts several phenomenological models (Valencia [21], XuCao [22], modified Valencia[14] and OPER[23, 24]) have been suggested for the analysis of the double pion production in NN collisions in the GeV energy range. These models differ a lot in number of resonances taken into account, the interaction mechanism and the role of interference between different contributions. The effective Lagrangian models (Valencia [21], XuCao [22] and modified Valencia [14]) predict that at energies near threshold the $\pi\pi$ production is dominated by the excitation of one of the nucleons into the Roper resonance $N^*(1440)P_{11}$ via σ-exchange. At higher energies the double $\Delta(1232)$ excitation is expected to be the dominant reaction mechanism for $\pi\pi$ production. The OPER model [23] based on the exchange of reggeized π have been successfully used to describe bubble chamber data[3] on $np \to np\pi^+\pi^-$ reaction at the momenta above 3 GeV/c. This model can be applied for description of $np \to np\pi^+\pi^-$ reaction at the momenta below 3 GeV/c by taking into account the mechanism of one baryon exchange(OBE).

New experimental data on double-pion production are needed to provide quantitative information on hadronic interactions, resonance excitations and resonance properties. In this work we present high statistics invariant mass and angular distributions on $\pi^+\pi^-$ and $\pi^-\pi^0$ production in quasi-free np collisions at an incident deuteron beam energy of 1.25 GeV/c obtained with the HADES spectrometer.

2. Experiment

The experimental data have been obtained using the High Acceptance Di-Electron Spectrometer (HADES) [25] located at the GSI Helmholtzzentrum für Schwerionenforschung in Darmstadt,

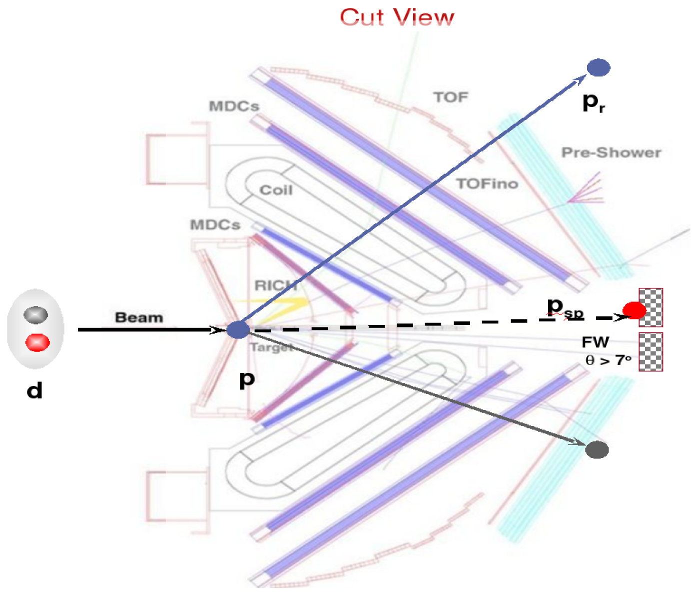

Figure 1: Cut through two sectors of the HADES spectrometer. The magnet coils are projected onto the cut plane to visualize the toroidal magnetic field. A schematic view of the quasi-free $n+p$ reaction is shown.

Germany. The HADES is a modern multi-purpose detector currently operating in the region of kinetic beam energies of up to 2 A·GeV for nucleus-nucleus collisions. The schematic view of the HADES spectrometer is presented in Fig. 1. The spectrometer which was primarily designed to measure di-electrons, offers excellent hadron identification capabilities. Geometrically the spectrometer is divided into 6 identical sectors covering the full azimuthal angle and polar angles from 18° to 85° measured relative to the beam direction. Each sector of the spectrometer contains a Ring Imaging Cerenkov detector (RICH) operating in a magnetic field-free region, inner multi-wire drift chambers (MDCs) in front of the magnetic field, outer MDCs behind the magnetic field, TOF and TOFino time-of-flight detectors and a electromagnetic cascade detector (Pre-Shower). The investigation of the quasi-free np- reactions with the deuteron beam is performed by using a Forward Wall (FW) scintillator hodoscope by registering the spectator protons. The FW is an array which consists of nearly 300 scintillating cells each 2.54 cm thick. During the dp- experiment the FW was located 7 meters downstream the target covering polar angles from 0.33° up to 7.17°. A Monte Carlo simulation for deuteron-proton breakup has shown that approximately 90% of all spectator protons are within the FW acceptance [2]. While a detailed description of the setup can be found in [25], we summarize here only the features relevant for the present analysis.

In the presented experiments the deuteron beam with intensities up to 10^7 particles/s and 1.25 GeV/c kinetic energy were directed to a 5 cm long liquid-hydrogen target of 1% interaction probability. The momenta of the produced particles were deduced from the hits in the four drift chamber planes (two before and two after the magnetic field zone) using a Runge-Kutta algorithm [25]. The momentum resolution was 2-3% for protons and pions and 1-2% for electrons, depending on momentum and angle [25]. The start signal for the time measurements was taken from the fastest signal from the scintillator wall. To reconstruct the time-of-flight for each particle, a dedicated method was developed [25], using the identification of one reference particle, the time-of-flight of which can be calculated. The time-of-flight reconstruction algorithm was checked in a dedicated experiment with a low beam intensity using a START detector [25]. The charge hadrons were selected from leptons by using RICH detector, together with TOF/TOFINO and Pre-Shower detectors. Quasi-free np- interactions have been selected by the detection of the proton spectators with the scattering angles $\leq 2^\circ$ and the momenta between 1.7 GeV/c and 2.3 GeV/c reconstructed from the time-of-flight measurement in FW. The selection of $np \to np\pi^+\pi^-$ and $np \to pp\pi^-\pi^0$ channels was based on identification of three detected hadrons where one of them has the negative momentum polarity. The particle identification was based on the event hypotheses where any of the three selected hadrons has been used as the reference particle. The reference particle time-of-flight was calculated using its values of the reconstructed momentum and trajectory length. The velocities of other two particles were then deduced, using only the time-of-flight difference with the reference particle. The applicability of this time-of-flight reconstruction algorithm was checked in a dedicated experiment with a low beam intensity by means of the START detector as discussed in [25]. The correlations between the velocity and reconstructed momentum for all three particles were taken into consideration to reject the wrong hypotheses. The addition criteria on squared missing mass of $pp\pi^-$ was applied in the case of selection the $np \to pp\pi^-\pi^0$ channel to reject $np \to pp\pi^-$ events.

3. Results

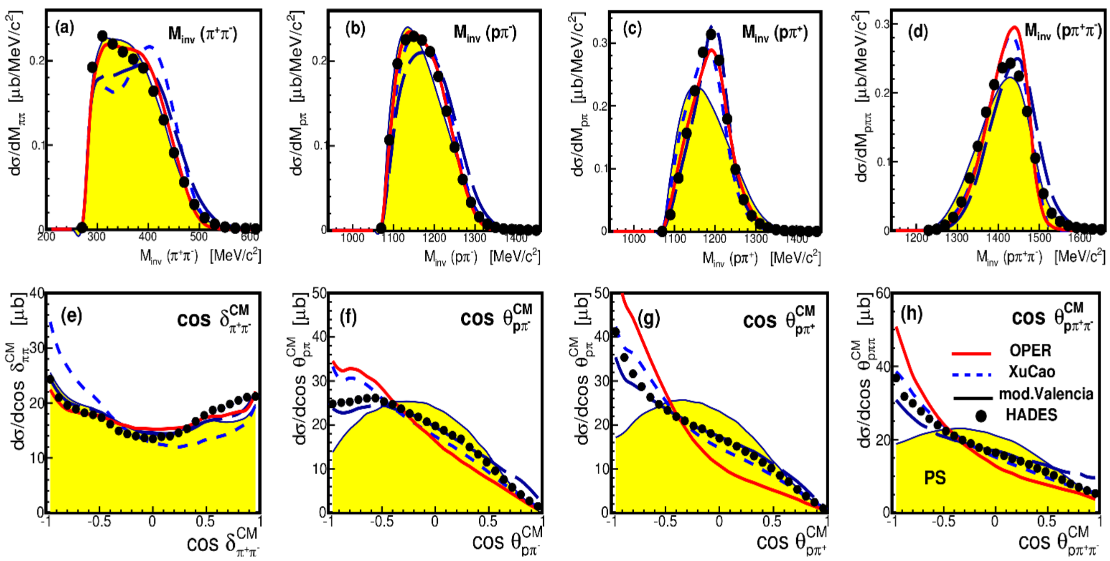

Figure 2: Distributions of the $\pi^+\pi^-$, $p\pi^-$, $p\pi^+$ and $p\pi^+\pi^-$ invariant masses for the $np \to np\pi^+\pi^-$ reaction at 1.25 GeV are presented in a), b), c) and d) panels, respectively. e) - opening angle of $\pi^+\pi^-$ in the np rest frame, f), g), h) - polar angles of $p\pi^-$, $p\pi^+$, $p\pi^+\pi^-$ in the np rest frame, respectively. The experimental data are shown with solid symbols. The theoretical predictions within HADES acceptance from Refs. [24], [22], [16] are given by the solid, dashed and long-dashed lines, respectively. The shaded areas show the phase-space distributions.

The data on the differential cross section and angular distributions for the $np \to np\pi^+\pi^-$ reaction at 1.25 GeV corrected for the reconstruction efficiency are presented by the solid circles in Fig. 2. The data error bars include the statistical errors only. The normalization of the experimental yield has been performed using the simultaneously measured quasi-elastic pp- scattering yield [26]. The experimental data are compared with OPER [24], modified Valencia [16] and Cao et al. [22] models. The theoretical predictions of modified Valencia [16], Cao et al. [22] and OPER [24] models inside HADES acceptance are presented in Fig. 2 and Fig. 3 by the long-dashed, dashed and solid lines, respectively. All the calculations are normalized to the number of the events in the experimental spectra. The shaded areas show the phase-space distributions. The calculations [16] and [22] predict that the $\pi\pi$ production for the $np \to np\pi^+\pi^-$ reaction at 1.25 GeV is mainly caused by the $\Delta\Delta$ excitation, while according to the OPER model [24] the $\Delta\Delta$ and OBE gives commensurable contributions. The comparison of experimental data with theoretical predictions in Fig. 2 and Fig. 3 show that none of the models can describe all distributions, simultaneously. The experimental $p\pi^-$, $p\pi^+$ and $p\pi^+\pi^-$ invariant mass distributions demonstrate the resonant nature of the spectra shifted to the higher masses in comparison with the phase-space calculations. The most prominent resonance structure is observed for the $p\pi^+$ subsystem, where the position of the maximum in the experimental distribution roughly corresponds to the Δ^{++} mass. The theoretical models [22, 16, 24] reproduce the shape and position of the maximum of the experimental $M_{p\pi^+}$ distribution. However, the modified Valencia model [16] do not describe the shape of the experimental $M_{p\pi^-}$ and $M_{p\pi^+\pi^-}$ distributions and predict that the maxima of these spectra are shifted to the larger masses, while the calculations by Cao et al. [22] and OPER model [24] reproduce these spectra. The most significant difference between the obtained data and theoretical predictions ([16], [22]) is observed for the $\pi^+\pi^-$ invariant mass distribution, where enhancement is present at low $M_{\pi^+\pi^-}$ values. Similar enhancement has been observed earlier for the $\pi^0\pi^0$ system in the

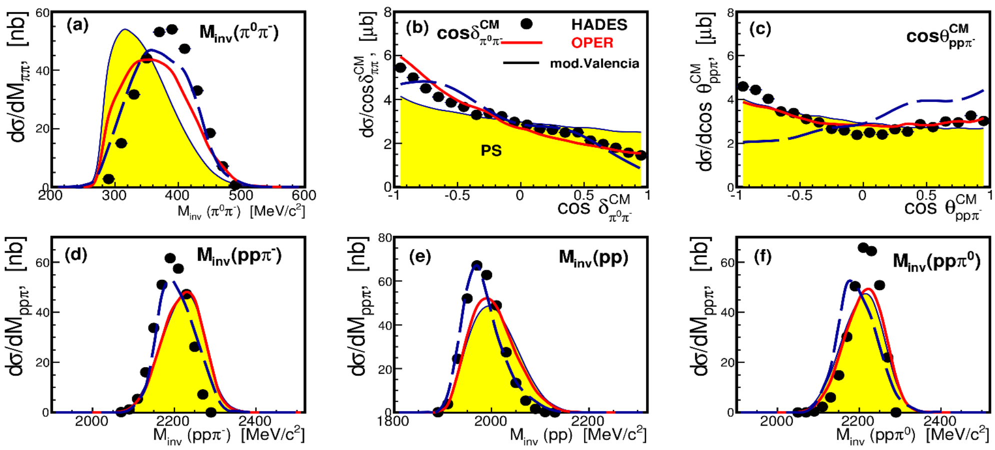

Figure 3: Distributions of the $\pi^-\pi^0$, $pp\pi^-$, pp and $pp\pi^0$ invariant masses for the $np \to pp\pi^-\pi^0$ reaction at 1.25 GeV are presented in a), d), e) and f) panels, respectively. b) - opening angle of $\pi^-\pi^0$ in the np rest frame, c) - polar angle of $pp\pi^-$ in the np rest frame. The experimental data are shown with the solid symbols. The theoretical predictions within HADES acceptance from Refs. [24], [17] are given by the solid and long-dashed lines, respectively. The shaded areas show the phase-space distributions.

$pp \to pp\pi^0\pi^0$ reaction at the energies above 1.0 GeV [15, 18]. The modified Valencia model [16], which was successfully used to describe $\pi\pi$ production in pp collision [15, 18] and Cao et al. [22] calculations don't reproduce the $\pi^+\pi^-$ in np collision. The OPER model with the using so called "hanged" diagrams [24] predicts some enhancement at low $\pi^+\pi^-$ masses, but it fails in reproducing the angular distributions (see Fig. 2 f),g),h)).

The Fig. 3 presents preliminary results for the $np \to pp\pi^-\pi^0$ reaction at 1.25 GeV. Experimental data showed by solid circles are compared with OPER [24] and modified Valencia model with taking into account s-channel d^* resonance amplitude [17]. The shaded areas show the phase-space distributions. The modified Valencia model inside HADES acceptance [17] gives a good description of pp and $pp\pi^-$ invariant mass spectra. However this model doesn't describe the polar angle distribution of $pp\pi^-$ in the np rest frame. The OPER model [24] well describes the angular distributions (see Fig. 3 b),c)), while the pp, $pp\pi^-$, $pp\pi^0$ invariant masses show phase-space like behavior and deviates from experimental data.

In the summary, we have presented high precision exclusive measurements of the $np \to np\pi^+\pi^-$ and $np \to pp\pi^-\pi^0$ reactions at 1.25 GeV with the HADES spectrometer. The specific acceptance of HADES favors to the non-peripheral region of this reaction corresponding to the intermediate and large squared momentum transfer. It allows one to test and specify various models of double-pion production in NN-interactions. The deviations for the shapes of some differential distributions still leave an opportunity for further optimization of the existing models.

Acknowledgments

We acknowledge valuable discussions with Dr. T. Skorodko and are particularly indebted to her and Dr. Xu Cao for the provided calculations.

References

[1] S. Leupold, V. Metag and U. Mosel, *Hadrons in strongly interacting matter*, *Int. J. Mod. Phys.* **E 19** (2010) 147.

[2] G. Agakishiev *et al.* (HADES Collab.), *Origin of the low-mass electron pair excess in light nucleus-nucleus collisions*, *Phys. Lett.***B690**, (2010) 118.

[3] C. Besliu *et al.*, YaF, **43** (1986) 888-892;

[4] A. Baldini, V. Flamino, W.G. Moorhead, and D. R. O. Morrison (eds.), Landolt-Bornstein, *Numerical Data and Functional Relationships in Science and Technology*, Vol. 12, (Springer-Verlag, Berlin, 1988).

[5] J. Johanson *et al.*, *Two-pion production in proton-proton collisions near threshold*, *Nucl. Phys.* **A712** (2002) 75;

[6] W. Brodowski et al., *Exclusive Measurement of the $pp \to pp\pi^+\pi^-$ Reaction Near Threshold*, *Phys. Rev. Lett.* **88** (2002) 192301;

[7] E. Doroshkevich et al., *Study of baryon and search for dibaryon resonances by the $pp \to pp\pi^+\pi^-$ reaction*, *Eur. Phys. J. A* **18** (2003) 171;

[8] S. Abd El-Bary *et al.*, *Two Pion Production in Proton-Proton Collisions with Polarized Beam Eur. Phys. J A* **18** (2008) 67;

[9] S. Abd El-Samad *et al.*, *On the production of $\pi^+\pi^-$ pairs in pp collisions at 0.8 GeV*, *Eur. Phys. J A* **42** (2009) 159;

[10] T. Tsuboyama *et al.*, *Double-pion production induced by deuteron-proton collisions in the incident deuteron momentum range 2.1-3.8 GeV/c*, *Phys. Rev. C* **62** (2000) 034001.

[11] V.V. Sarantsev *et al.*, *Measurement of the cross sections for $\pi^+\pi^-$ production in pp collisions at energies below 1 GeV*, *Phys. Atom. Nucl.***70** (2007) 1998.

[12] J. Patzold *et al.*, *Study of the $pp \to pp\pi^+\pi^-$ Reaction in the Low-Energy Tail of the Roper Resonance*, *Phys. Rev. C* **67** (2003) 052202;

[13] T. Skorodko *et al.*, *Excitation of the Roper resonance in single- and double-pion production in nucleon-nucleon collisions*, *Eur. Phys. J. A* **35** (2008) 317;

[14] T. Skorodko *et al.*, *Two-Pion Production in Proton-Proton Collisions: Experimental Total Cross Sections and their Isospin Decomposition*, *Phys. Lett.* **B679** (2009) 30.

[15] T. Skorodko *et al.*, *$\Delta\Delta$ Excitation in Proton-Proton Induced $\pi^0\pi^0$ Production*, Phys.Lett. **B695** (2011) 155.

[16] T. Skorodko *et al.*, *Exclusive Measurement of the $pp \to nn\pi^+\pi^+$ Reaction at 1.1 GeV*, *Eur.Phys.J.* **A47** (2011) 108.

[17] P. Adlarson *et al.*, *Measurement of the $pn \to pp\pi^0\pi^-$ reaction in search for the recently observed resonance structure in $d\pi^0\pi^0$ and $d\pi^+\pi^-$ systems*, *Phys. Rev.* **C88** (2013) 055208.

[18] P. Adlarson *et al.*, *$\pi^0\pi^0$ Production in Proton-Proton Collisions at T_p=1.4 GeV*, *Phys.Lett.* **B706** (2012) 256.

[19] M. Bashkanov *et al.*, *Double-Pionic Fusion of Nuclear Systems and the ABC Effect: Aproaching a Puzzle by Exclusive and Kinematically Complete Measurements*, *Phys. Rev. Lett.* **102** (2009) 052301.

[20] P. Adlarson *et al.*, *ABC Effect in Basic Double-Pionic Fusion — Observation of a new resonance?*, *Phys. Rev. Lett.* **106** (2011) 242302.

[21] L. Alvarez-Ruso, *et al.*, *Theoretical study of the $NN \to NNpipi$ reaction*, *Nucl. Phys. A* **633** (1998) 519.

[22] Xu. Cao, *et al.*, *Phenomenological analysis of the double pion production in nucleon-nucleon collisions up to 2.2 GeV*, *Phys. Rev. C* **81** (2010) 12.

[23] A.P. Jerusalimov, *Analysis of the Reaction: $np \to np\pi^+\pi^-$ from the Point of View of Oper-Model*, (2012) arXiv:[nucl-th/1203.3330]

[24] A.P. Jerusalimov, *Contribution of the "hanged" diagrams into the reaction $np \to np\pi^+\pi^-$*, (2012) arXiv:[nucl-th/1208.3982]

[25] G. Agakishiev *et al.*, *The High-Acceptance Dielectron Spectrometer HADES*, *Eur. Phys. J.* **A41** (2009) 243.

[26] D. Albers et al. (EDDA Collab.), *A Precision measurement of pp elastic scattering cross-sections at intermediate energies*, *Eur. Phys. J.* **A22** (2004) 125.