acta physica slovaca vol. 56 No. 3, 285 – 297 June 2006

ON THE $\pi\pi$ PRODUCTION IN FREE AND IN-MEDIUM NN-COLLISIONS: σ-CHANNEL LOW-MASS ENHANCEMENT AND $\pi^0\pi^0/\pi^+\pi^-$-ASYMMETRY[1]

M. Bashkanov[a], **T. Skorodko**[a], **C. Bargholtz**[l], **D. Bogoslawsky**[b], **H. Calén**[c], **F. Cappellaro**[d], **H. Clement**[a2], **L. Demiroers**[e], **E. Doroshkevich**[a], **C. Ekström**[c], **K. Fransson**[c], **L. Geren**[l], **J. Greiff**[c], **L. Gustafsson**[d], **B. Höistad**[d], **G. Ivanov**[b], **M. Jacewicz**[d], **E. Jiganov**[b], **T. Johansson**[d], **M.M. Kaskulov**[a], **S. Keleta**[d], **O. Khakimova**[a], **I. Koch**[d], **F. Kren**[a], **S. Kullander**[d], **A. Kupść**[c], **A. Kuznetsov**[b], **K. Lindberg**[l], **P. Marciniewski**[c], **R. Meier**[a], **B. Morosov**[b], **W. Oelert**[h], **C. Pauly**[e], **Y. Petukhov**[b], **A. Povtorejko**[b], **R.J.M.Y. Ruber**[c], **W. Scobel**[e], **R. Shafigullin**[m], **B. Shwartz**[i], **V. Sopov**[k], **J. Stepaniak**[g], **P.-E. Tegner**[l], **V. Tchernyshev**[k], **P. Thörngren-Engblom**[d], **V. Tikhomirov**[b], **A. Turowiecki**[j], **G.J. Wagner**[a], **M. Wolke**[d], **A. Yamamoto**[f], **J. Zabierowski**[g], **I. Zartova**[l], **J. Zlomanczuk**[d]

[a] Physikalisches Institut der Universität Tübingen, Tübingen, Germany
[b] Joint Institute for Nuclear Research, Dubna, Russia
[c] The Svedberg Laboratory, Uppsala, Sweden
[d] Uppsala University, Uppsala, Sweden
[e] Hamburg University, Hamburg, Germany
[f] High Energy Accelerator Research Organization, Tsukuba, Japan
[g] Soltan Institute of Nuclear Studies, Warsaw and Lodz, Poland
[h] Forschungszentrum Jülich, Germany
[i] Budker Institute of Nuclear Physics, Novosibirsk, Russia
[j] Institute of Experimental Physics, Warsaw, Poland
[k] Institute of Theoretical and Experimental Physics, Moscow, Russia
[l] Department of Physics, Stockholm University, Stockholm, Sweden
[m] Moscow Engineering Physics Institute, Moscow, Russia

(CELSIUS-WASA Collaboration)

Received 30 November 2005, in final form 5 January 2006, accepted 26 January 2006

The $pp \to NN\pi\pi$ and $pd \to {}^3$He $\pi\pi$ reactions have been measured exclusively at CELSIUS using the WASA 4π detector with pellet target system. With regard to the first reaction measurements have been conducted from the near-threshold region up to $T_p = 1.45$ GeV. For the double-pionic fusion to ^{3}He data have been taken at $T_p = 0.893$ GeV, where the maximum of the so-called ABC effect is expected. For the ^{3}He case a huge low-mass enhancement is observed in the $\pi^0\pi^0$ invariant mass $M_{\pi^0\pi^0}$, whereas only a moderate low-mass enhancement is seen in $M_{\pi^+\pi^-}$. The $pp \to pp\pi\pi$ reaction in the near threshold region can be well described by Roper excitation and chiral dynamics, however, at higher energies, in the $\Delta\Delta$

---

[1] Presented at the Workshop on Production and Decay of η and η' Mesons (ETA05), Cracow, 15–18 September 2005.
[2] E-mail address: clement@pit.physik.uni-tuebingen.de

region, data are at variance with theoretical predictions. In particular the $M_{\pi^+\pi^-}$ spectrum behaves phase-space like - in accordance only with the special $(\Delta\Delta)_{0^+}$ configuration - and the $M_{\pi^0\pi^0}$ spectrum develops a strong low-mass enhancement similar to the one observed in the ^{3}He $\pi^0\pi^0$ channel.

PACS: 13.75.Cs, 14.20.Gk, 14.40.Aq, 14.40.Cs

1 Introduction

Double pion production in NN collisions offers a variety of aspects concerning the dynamics of the total system as well as that of its subsystems $\pi\pi$, NN, πN, $\pi\pi N$ and πNN. The production process is expected to be dominated by excitation of one or of both participating nucleons. Close to threshold only the Roper resonance N^* (1440) excitation with its subsequent decay into $N\pi\pi$ can participate, since single Δ excitation is blocked due to its decay into a single pion only. Only at higher energies, $T_p > 1$ GeV, Δ excitation comes into play via the double Δ process.

First data on $\pi\pi$ production were taken by bubble chambers and with low statistics. First high-statistics data taken in single-arm magnetic spectrometer measurements revealed a first, very surprising feature: reactions leading to double-pionic fusion, i.e., bound nuclear systems in the final state, e.g., $pd \rightarrow ^3$He $\pi\pi$, result in a strong enhancement of strength at low invariant $\pi\pi$ masses as soon as the total charge of the $\pi\pi$ system is zero. This effect first found by Abashian, Booth and Crowe [1] and lateron termed ABC effect after the initials of the authors was originally thought to be due to an unusually strong $\pi\pi$ interaction, possibly stemming from an isoscalar resonance near $\pi\pi$ threshold. Lateron the effect was thought to originate from $\Delta\Delta$ excitation in the course of the process, since it is maximal at energies which are optimal for $\Delta\Delta$ excitation and since the theoretically [2] predicted double-hump structure in the $M_{\pi\pi}$ spectrum has not been at variance with the inclusive data of those days [3,4]. As we will see, the new exclusively measured data on $pd \rightarrow ^3$He $\pi^0\pi^0$ and $pd \rightarrow ^3$He $\pi^+\pi^-$ no longer support the double-hump structure, they instead show a large enhancement only at low $\pi\pi$ masses and - as a big surprise - in $\pi^0\pi^0$ much more pronounced than in $\pi^+\pi^-$.

For the basic reaction, i.e. the collision process between two free nucleons without the influence of a surrounding nuclear medium, first exclusively measured data of solid statistics have been obtained with PROMICE/WASA at CELSIUS in the near-threshold region [5–7]. There the $pp \rightarrow pp\pi^+\pi^-$ reaction can be well understood by excitation of the Roper resonance $N^*(1440)$ and its decay into the $N\sigma$ channel [5,6] as predicted previously [8] - with σ denoting the scalar-isoscalar configuration $(\pi\pi)_{I=l=0}$. Here the decay of the Roper resonance may proceed either directly via the route $N^* \rightarrow N\sigma$ or indirectly with intermediate Δ excitation via the route $N^* \rightarrow \Delta\pi \rightarrow N\sigma$. The interference of both routes causes a characteristic pattern in the observables, in particular in the $M_{\pi\pi}$ spectrum, which has been exploited to determine [6] the relative branching ratio of these decay routes.

Alternatively the near-threshold data can be fitted very well within the concept of chiral dynamics, where the σ meson is generated dynamically by $\pi\pi$ rescattering [9]. With increasing incident energies the competitive process of a $\Delta\Delta$ excitation in the NN system comes into play and finally should dominate the reaction for $T_p > 1$ GeV. According to predictions [8] the distribution of the invariant mass $M_{\pi^+\pi^-}$ should develop a double-hump structure similar to that calculated for the ABC effect in nuclei [2,10].

Since there are no data of solid statistics to test these predictions for the basic NN collision process, we have carried out exclusive measurements for both the $pp\pi^+\pi^-$ and $pp\pi^0\pi^0$ channels. For the latter there have been no previous exclusive data at all. As a first surprise we find - as we will show in the following - that for $T_p > 1$ GeV the $M_{\pi^+\pi^-}$ distributions are phase-space like contrary to predictions. As a second even bigger surprise we find the $M_{\pi^0\pi^0}$ distributions to be much different by exhibiting a strong enhancement at small invariant masses - being reminiscent of the ABC effect or the effect of Bose-Einstein correlations, respectively.

As a starting point for looking into the $\pi\pi$ production process in the presence of a nuclear medium we have carried out exclusive measurements of the reactions $pd \rightarrow^3$He $\pi^+\pi^-$ and $pd \rightarrow^3$He $\pi^0\pi^0$ at $T_p = 0.893$ GeV [11, 12], i.e. at an energy where the maximum ABC effect has been observed in previous inclusive measurements [3]. Again we observe a $\pi\pi$ low-mass enhancement - in $\pi^0\pi^0$ much bigger than in $\pi^+\pi^-$, however, we do not observe a $\pi\pi$ enhancement at high masses, i.e. no double-hump structure as predicted in $\Delta\Delta$ models and as suggested by inclusive measurements. Measurements on the next larger nucleus ^{4}He have been carried out by utilizing the reactions $dd \rightarrow^4$He $\pi^+\pi^-$ and $dd \rightarrow^4$He $\pi^0\pi^0$. This experiment has been the last one before final shutdown of the CELSIUS ring in June 2005. The analysis of these data is still in progress.

2 Experiment

The measurements have been carried out at the CELSIUS storage ring in the energy range of $T_p = 0.775 - 1.45$ GeV using the WASA detector (Fig. 1) together with the pellet hydrogen target system [13]. The detector has nearly full angular coverage for the detection of charged and uncharged particles. The forward detector consists of a straw tracker unit followed by plastic scintillator quirl and range hodoscopes, whereas the central detector comprises in its inner part a plastic scintillator barrel containing a minidrift chamber for tracking, and in its outer part a thin-walled superconducting magnet surrounded by an electromagnetic calorimeter consisting of 1012 CsI(Na) crystals. In these runs triggers had been set to allow for simultaneous measurements of single pion, double pion and also η-production - the latter only for $T_p \geq 1.36$ GeV. In case of $\pi\pi$ production either the two protons or the ^{3}He particles have been detected in the forward detector, whereas the gammas and charged pions, respectively have been detected in the central detector. Thus gammas have been detected only for $\Theta^{lab} > 20°$. This causes some efficiency loss, but no loss in the phase-space coverage, since these gammas originate from π^0 particles decaying in all directions. Some loss of phase-space coverage, however, is unavoidable in the case of charged pions, which in the present study also have been detected for $\Theta^{lab} > 20°$ only, and in case of protons, which due to the trigger conditions used have the restriction $\Theta^{lab} < 18°$.

As an example of the experimental situation we show in Fig. 2 the $\pi^0\pi^0$ reconstruction from the observation of four gammas. In the $M_{\gamma\gamma} - M_{\gamma\gamma}$ plane the $\pi^0\pi^0$ peak is seen to sit upon essentially no background. By requiring all particles of an event to be measured in their full four-momenta we can apply kinematic fits for each event with 4 overconstraints in case of $\pi^+\pi^-$ production and 6 overconstraints in case of $\pi^0\pi^0$ production, respectively.

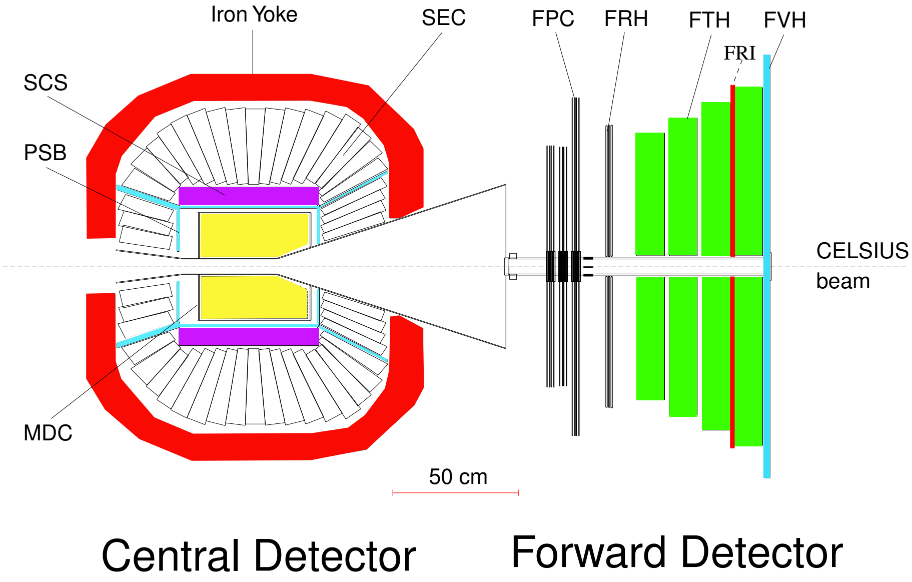

Fig. 1. Plan view of the WASA detector: The SuperConducting Solenoid (SCS) and the iron yoke for the return path of magnetic flux is shown shaded. Plastic scintillators are situated in the Plastic Scintillator Barrel (PSB), Forward Window Counters (FWC), Forward Trigger Hodoscope (FTH), Forward Range Hodoscope (FRH), Forward Range Intermediate Hodoscope (FRI), Forward Veto Hodoscope (FVH) and Backward Veto Counters (BVC). Cesium Iodide scintillators are situated in the Scintillator Electromagnetic Calorimeter (SEC). Proportional wire drift tubes, straws, make up the Mini Drift Chamber (MDC) and the Forward Proportional Chambers (FPC).

3 Results

3.1 $pp \longrightarrow pp\pi^+\pi^-$

At energies $T_p < 1$ GeV the data are consistent with the finding in the near-threshold region, i.e., they are well described by Roper excitation and its decay as shown in Refs. [5, 6]. In particular, the $M_{\pi^+\pi^-}$ spectrum is enhanced towards large $\pi^+\pi^-$ masses as associated with the $N^* \to \Delta\pi$ decay branch. At energies $T_p > 1$ GeV, where the $\Delta\Delta$ process is expected [8] to take over, the differential distributions change indeed. In fact, the dominance of the $\Delta\Delta$ process can be viewed by observing the $M_{p\pi^+}$ and $M_{p\pi^-}$ spectra. Whereas for $T_p < 1$ GeV the $M_{p\pi^+}$ spectrum is much more affected by Δ excitation than the $M_{p\pi^-}$ spectrum due to the circumstance that Δ^{++} is much more favored in the $N^* \to \Delta\pi$ decay than Δ^0, both Δ need to be equally excited in the $\Delta\Delta$ process - as indeed the data show for $T_p > 1$ GeV.

Following the theoretical predictions [8] we should expect the $M_{\pi^+\pi^-}$ spectrum to develop a double-hump structure as soon as the $\Delta\Delta$ signature gets apparent in the $M_{p\pi}$ spectra. However, contrary to these expectations and also different from the situation for $T_p < 1$ GeV the measured $M_{\pi^+\pi^-}$ spectra rather become phase-space like. Also the pion angular distributions stay flat -

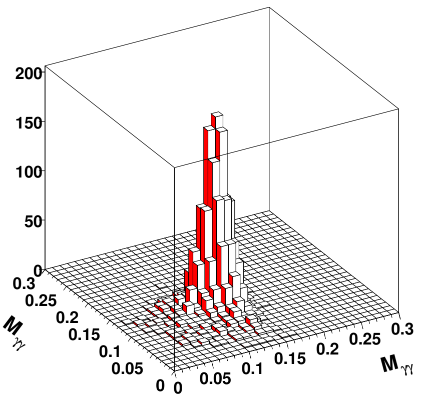

Fig. 2. Data from $pp \to pp\pi^0\pi^0$ measurements at $T_p = 0.775$ GeV. Lego plot of $M_{\gamma\gamma}$ versus $M_{\gamma\gamma}$ (both in units of GeV/c^2) from the 4 detected gammas per event. All possible two-by-two combinations are considered with the optimal one being selected and plotted in the figure. Hence there is no combinatorial background. The vertical scale denotes counts per bin.

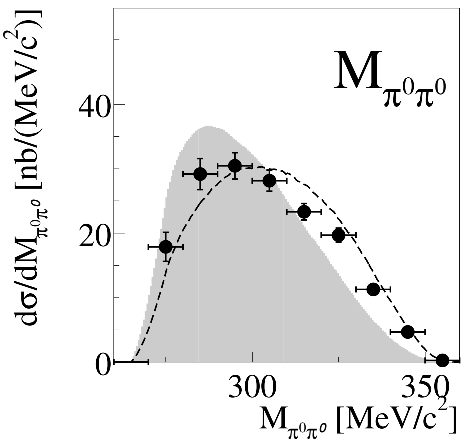

Fig. 3. $M_{\pi^0\pi^0}$ spectrum resulting from the data analysis at $T_p = 0.775$ GeV. The data (solid dots) are compared to phase-space calculations (shaded area) and calculations for Roper excitation and decay (dashed lines). The Roper decay parameters have been adjusted for optimum reproduction of the $pp \to pp\pi^+\pi^-$ data at identical incident energy [6].

again in contrast to the predictions, which assume the $\Delta\Delta$ system to couple to all possible spin-parity combinations. Since $\Delta\Delta$ configurations with large angular momentum have the highest statistical weights, strong angular dependences result in such calculations. On the other hand the phase-space like data for $M_{\pi^+\pi^-}$ and Θ_π distributions suggest that only a single $\Delta\Delta$ dibaryonic configuration is excited in this process, namely the one with $(I, J^P) = (1, 0^+)$, which is equivalent to having just the ${}^1S_0$ partial wave at work in this $\pi\pi$ production process. In fact, from the success of Roper and chiral dynamics descriptions for $T_p < 1$ GeV the ${}^1S_0$ partial wave is already known to be the dominant partial wave responsible for $\pi\pi$ production at low energies. Nevertheless it is astonishing that this obviously holds also in case of higher energies. Since π-exchange does not lead to such an unique preference of the ${}^1S_0$ partial wave, heavy meson exchange could be responsible for the observed behavior.

The produced $\pi^+\pi^-$ pair principally may have isospin I = 0, 1, 2. Also by Bose symmetry isovector $\pi^+\pi^-$ pairs must be in an odd angular momentum state, i.e. need to be in relative p-waves and hence should cause non-flat pion angular distributions. Since this is not the case as noted above, we conclude that I=1 contributions must be small in the $\pi^+\pi^-$ channel.

3.2 $pp \to pp\pi^0\pi^0$

Since we deal here with identical particles in the $\pi\pi$ pair, only even angular momenta are allowed between the two bosons and therefore also the isospin of the pair can only be I = 0 or 2. Our data for the $\pi^0\pi^0$ channel exhibit features, which basically are similar to those in the $\pi^+\pi^-$ channel as expected from isospin invariance - if isovector contributions to the latter channel are small as pointed out above and if isotensor components are also small in both channels - as discussed below.

In this context it comes as a surprise that at all energies we observe a systematic shift of strength in the $M_{\pi^0\pi^0}$ spectrum (relative to what is expected from the corresponding $M_{\pi^+\pi^-}$ spectrum) towards small invariant masses. As an example we show in Fig. 3 the $M_{\pi^0\pi^0}$ spectrum obtained at $T_p = 0.775$ GeV. Relative to phase space the data are enhanced towards high $\pi\pi$ masses as expected from excitation and decay of the Roper resonance as well as from chiral dynamics as discussed above. Such calculations indeed give a good description of the data [14] except of a small, but systematic shift between data and calculations (see Fig. 3). This small systematic shift increases for higher energies and for $T_p > 1$ GeV it results even in a peculiar enhancement at low $M_{\pi^0\pi^0}$, which is correlated with small opening angles $\delta_{\pi^0\pi^0}$ between the two pions in the overall center of mass system, i.e. the pions of the enhancement region move essentially in parallel. As an example the situation for $\pi^+\pi^-$ and $\pi^0\pi^0$ channels is shown in Fig. 4 for $T_p = 1.1$ GeV.

In order to shed more light onto the nature of this enhancement, we next construct the so-called correlation function $R(M_{\pi^0\pi^0})$ by dividing the observed $M_{\pi^0\pi^0}$ spectrum by that expected from the observed $M_{\pi^+\pi^-}$ spectrum in the following way:

Due to the π^0 / $\pi^\pm$ mass difference $\pi^0\pi^0$ and $\pi^+\pi^-$ thresholds differ by as much as 9 MeV. Hence we cannot simply divide $\pi^0\pi^0$ and $\pi^+\pi^-$ spectra by each other, but rather have to account properly for the pion mass differences. For $T_p < 1$ GeV the Roper ansatz provides a good description for the $pp\pi^+\pi^-$ channel. Hence we use this ansatz to calculate the expected $M_{\pi^0\pi^0}$ spectrum. For $T_p \geq 1$ GeV the $M_{\pi^+\pi^-}$ data are compatible with phase space and we can obtain $R(M_{\pi^0\pi^0})$ just by dividing the $M_{\pi^0\pi^0}$ data by the phase-space distribution for this spectrum. The normalization of $R(M_{\pi^0\pi^0})$ as shown in Fig. 4 is chosen such as to have unity for large $M_{\pi^0\pi^0}$ values. With this construction we silently assume the $\pi\pi$ spectra to be of isoscalar nature, which has to be justified. Indeed, an isospin decomposition [15] of the $NN\pi\pi$ production cross sections shows that the $I_{\pi\pi} = 2$ component is strongly suppressed in $pp\pi^0\pi^0$ and $pp\pi^+\pi^-$ already by isospin coupling. A further strong suppression comes from the dominant reaction mechanism via $\Delta\Delta$. Experimentally this is confirmed by the very small cross sections in the $nn\pi^+\pi^+$ channel [16]. For $I_{\pi\pi} = 1$ there is no contribution from the $\Delta\Delta$ process and only a tiny contribution from Roper excitation can be expected. Indeed, as already stated above, the observed flat π angular distributions exclude any major p-wave contributions between the pions, which would be a consequence of $I_{\pi\pi} = 1$.

After having convinced ourselves that the $M_{\pi^0\pi^0}$ and $M_{\pi^+\pi^-}$ spectra are essentially isoscalar, we discuss now the correlation function $R(M_{\pi^0\pi^0})$, which exhibits an enhancement of about a factor of two at $M_{\pi^0\pi^0} = 2m_{\pi^0}$ and decreases to unity within the following 30-40 MeV. This behavior resembles very much that known from Bose-Einstein correlations for identical bosons, the quantum mechanical analogon of the Hanbury-Brown-Twiss effect [17, 18]. Since this effect only occurs, if identical bosons are emitted from a chaotic source, i.e., with no phase relation

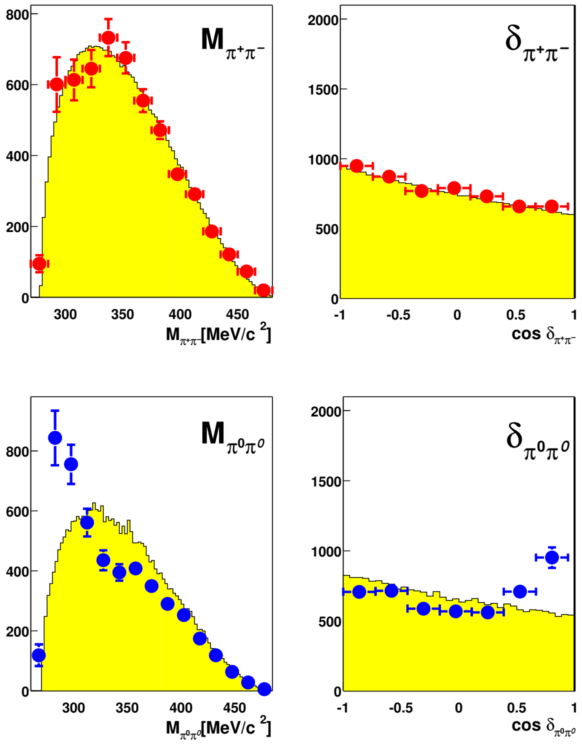

Fig. 4. Preliminary results for the distribution of invariant $\pi\pi$ masses $M_{\pi\pi}$ and $\pi\pi$ opening angles $\delta_{\pi\pi}$ from $pp \longrightarrow pp\pi^+\pi^-$ (top) and $pp \longrightarrow pp\pi^0\pi^0$ (bottom) reactions at $T_p = 1.1$ GeV. The phase space distributions are indicated by the shaded histograms. Note the peculiar behavior at small invariant masses and small opening angles in the $\pi^0\pi^0$ channel. The vertical scales are in arbitrary units.

between the emitted bosons, the interpretation of our findings in such a scenario would mean that we have two Δs excited by the initial pp collision, which afterwards decay independently by each emitting a π^0. The range of the enhancement in $R(M_{\pi^0\pi^0})$ is then correlated to the size of source [18]. From a fit to $R(M_{\pi^0\pi^0})$ in Fig. 5 we obtain a source size of $r_0 \approx 1.5 fm$, which is a very reasonable value for hadron production in NN collisions and also in comparison with corresponding values obtained in heavy ion, $p\overline{p}$ and other reactions [17]. Moreover, the enhancement factor of two at $M_{\pi^0\pi^0} = 2m_{\pi^0}$ constitutes the maximum enhancement possible in this scenario and means that the two π^0 particles are emitted totally incoherently. If true then the $NN\pi\pi$ system would constitute a minimal system, where Bose-Einstein correlations occur with maximum incoherence.

On the other hand one has to worry, whether such a minimal system in a well-defined quantum mechanical state principally can meet the requirements for Bose-Einstein correlations. In particular the deduced value for the source size means that the two Δs are within their inter-

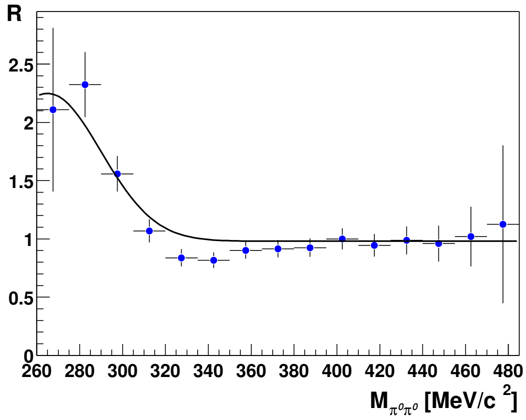

Fig. 5. Correlation function $R(M_{\pi^0\pi^0})$ deduced from the data at $T_p = 1.1$ GeV for $\pi^0\pi^0$ and $\pi^+\pi^-$ channels assuming $I_{\pi\pi} = 0$ (see text). The solid line gives a Gaussian fit to the correlation function.

action range when decaying - and the question naturally arises, whether such a situation can lead to independent decays of the Δs. From the experimental point of view the crucial experiment to settle this question would be an exclusive measurement of the $pp \rightarrow nn\pi^+\pi^+$ channel, which again has identical bosons in the exit channel and proceeds via the same intermediate $\Delta\Delta$ configuration as the $pp\pi^0\pi^0$ channel. If the above interpretation is correct, then we should again observe such an enhancement in the $M_{\pi^+\pi^+}$ spectrum. Unfortunately, this channel is very difficult to access experimentally and only a few events have been reported so far in inclusive bubble-chamber measurements [16]. Since the WASA detector also is sensitive to neutrons, we have started analysis of exclusive data for this reaction. First very preliminary results show no particular low-mass enhancement in $M_{\pi^+\pi^+}$.

From the discussion above about isospin decomposition we have seen that this enhancement must be dominantly isoscalar. Since this enhancement is at small $M_{\pi^0\pi^0}$ masses, only s-waves can participate. Hence this phenomenon must be dominantly scalar-isoscalar in nature. Therefore, as an alternative to the Bose-Einstein correlation scenario we also might consider a σ-channel phenomenon as origin for the observed enhancement.

Such a phenomenon could possibly be a state right at the $\pi^0\pi^0$ threshold or a dynamical isospin breaking due to virtual $\pi\pi$ loops. The latter arises from the fact that $\pi^0\pi^0$ and $\pi^+\pi^-$ thresholds are different because of the isospin breaking in the pion masses. In this gap between the thresholds the isospin obviously is not well defined. Above the $\pi^+\pi^-$ threshold the $\pi\pi$ loops may decay both into $\pi^+\pi^-$ and $\pi^0\pi^0$ channels. However, below $\pi^+\pi^-$ threshold the $\pi\pi$ loops have access solely to the $\pi^0\pi^0$ channel. Since from isospin conservation $\pi^+\pi^-$ and $\pi^0\pi^0$ pairs must be equally distributed in the virtual loops and since below $\pi^+\pi^-$ threshold all $\pi\pi$ loops have to decay into the $\pi^0\pi^0$ channel, we expect an enhancement of a factor two in the $M_{\pi^0\pi^0}$ distribution up to the $\pi^+\pi^-$ threshold. Because at small $\pi^+\pi^-$ masses the phase space volume is much smaller than that for the $\pi^0\pi^0$ channel, we might expect to have some - though declining - enhancement even for $M_{\pi^0\pi^0} > 2m_{\pi^+}$. On a qualitative level we see that this scenario leads to a similar enhancement as the Bose-Einstein scenario. Again the $nn\pi^+\pi^+$ channel will be very decisive here, since a $\pi\pi$ loop enhancement is restricted to the σ channel. We note that a similar enhancement due to $\pi\pi$ loops has been predicted [19,20] and also measured [21] recently for $\gamma N \to N\pi^0\pi^0$ in the total cross section close to threshold.

$M_{\pi^0\pi^0}$ distributions in the energy range discussed here have recently also been obtained from $\gamma p \to p\pi^0\pi^0$ [22] and $\pi^- p \to n\pi^0\pi^0$ [23]. Whereas the measurements of the first reaction do not indicate any major low-mass enhancement relative to phase space, the high-statistics measurements of the latter reaction do in fact exhibit some low-mass enhancement (Fig. 7 of [23]). Unfortunately there are no precise data for the corresponding $\pi^+\pi^-$ channel to compare with. Moreover, for $\gamma p \to p\pi^+\pi^-$ the production process is much different from that in $\gamma p \to p\pi^0\pi^0$ due to Kroll-Rudermann and pion-pole terms.

3.3 $pp \to d\pi^+\pi^0, np\pi^+\pi^0, nn\pi^+\pi^+$

The present data base on these channels is very scarce. As already noted above for the $nn\pi^+\pi^+$ channel, which is particularily hard to access experimentally, only few inclusive bubble chamber events have been reported. Analysis of WASA data for this channel is in progress.

For the $np\pi^+\pi^0$ channel there are first semi-exclusive data in the near-threshold region from PROMICE/WASA [7]. The deduced integral cross sections are larger by a factor of two than predicted [8]. Since in these calculations the $pn\pi^+\pi^0$ channel is essentially fed by the spinflip part of the Roper decay, which in turn is firmly connected to its non-spinflip part fixed by the analysis of $pp\pi^+\pi^-$ and $pp\pi^0\pi^0$ channels, the cause for this failure is presently not clear. Possibly the strong pn final state interaction not included in these calculations leads to an enhanced cross section in the threshold region.

The analysis of the data taken at WASA for the $\pi^+\pi^0$ channels is still in progress. Preliminary results for the $d\pi^+\pi^0$ channel at $T_p = 1100$ MeV show no enhancement at low $M_{\pi^+\pi^0}$ values, which is consistent with the statement made in chapter 3.2 that the observed $\pi\pi$ low-mass enhancement is of isoscalar nature.

3.4 $pd \to {}^3$He $\pi^0\pi^0$

In this reaction ^{3}He acts as an isospin filter excluding $I_{\pi\pi} = 2$ for the $\pi\pi$ system. In addition, from Bose symmetry $I_{\pi\pi} = 1$ is forbidden for the $\pi^0\pi^0$ system. Hence the $\pi^0\pi^0$ pair is exclusively in an isoscalar state here. The data taken at WASA [11,12] constitute not only the first exclusive data but the first data at all for this channel.

Fig. 6 shows the 3D plot of lab angle versus lab energy of the ^{3}He particles detected in the forward detector - before kinematic fit and any demand on other particles in the event. Whereas for single π^0 production ^{3}He particles are detected only in a very limited angle and energy range of phase space, the ^{3}He particles stemming from $\pi\pi$ production are covered over the full kinematical range up to ^{3}He angles $\Theta^{cm}_{^3He} \leq 90°$. In Fig. 6 the band for single π^0 production is seen to be well separated from the continuum for $\pi\pi$ production. Also immediately evident is a large accumulation of events near the kinematical limit for $\pi\pi$ production, i.e. in the region corresponding to small invariant $\pi\pi$ masses. Since detector acceptance and efficiency are flat

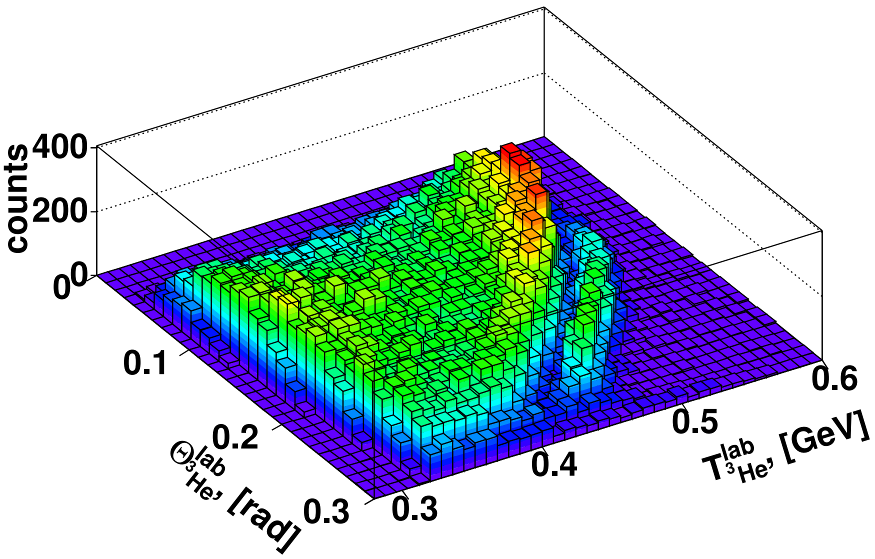

Fig. 6. Lego plot of lab angle $\Theta^{lab}_{^3He}$ versus lab energy $T^{lab}_{^3He}$ particles measured in the forward detector.

over the corresponding phase-space region in Fig. 6, this feature obviously is in accord with a strong ABC enhancement present in these data. In fact, if we slice Fig. 6 into angular bins, then we obtain spectra which resemble very much those measured at Saclay [3], however, with the exception that we do not see the strong additional rise at large missing masses present in the Saclay data.

Next we demand that the ^{3}He particles are accompanied by 2 or 4 gammas from π^0 decay or by a $\pi^+\pi^-$ pair registered in the central detector. As expected from the discussion of Fig. 6 we see a strong enhancement at low $\pi\pi$ masses towards threshold as displayed in Figs. 7 and 8 showing the distributions of the invariant mass $M_{\pi\pi}$. Since low invariant masses belong to $\pi\pi$ pairs with small relative momentum, such pairs move essentially in parallel in lab and overall cms what we also observe experimentally in the distribution of the $\pi\pi$ opening angle [11]. For $M_{\pi\pi} < 0.34$ GeV, i.e. the region of the enhancement, the angular distribution in the $\pi\pi$ subsystem (Jackson frame) turns out to be flat [11] in accordance with pure s-waves, which means that the enhancement is of scalar nature.

3.5 $pd \rightarrow {}^3\mathrm{He}\,\pi^+\pi^-$

The result for the $M_{\pi^+\pi^-}$ spectrum is shown in Fig. 8. The most striking feature is that, though there is still some low-mass enhancement visible, it is much smaller than in the $\pi^0\pi^0$ channel. The discrepancy between the low-mass distributions for $M_{\pi^0\pi^0}$ and $M_{\pi^+\pi^-}$ looks, indeed, like a substantial isospin violation in this mass range. In fact, when plotting both distributions on top

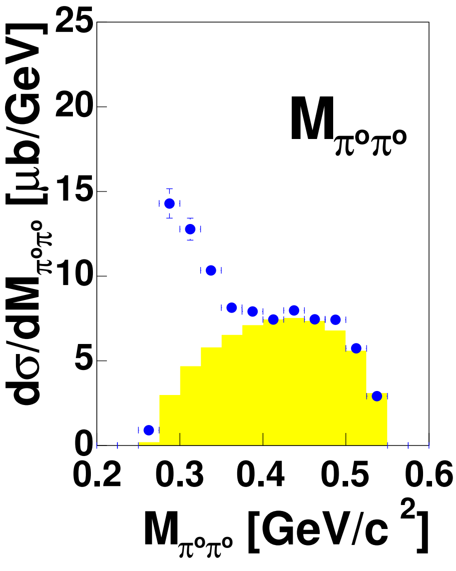

Fig. 7. Differential cross section of the distribution of the invariant mass $M_{\pi^0\pi^0}$ for the reaction $pd \to {}^3$He $\pi^0\pi^0$. The shaded area shows the phase space distribution for comparison.

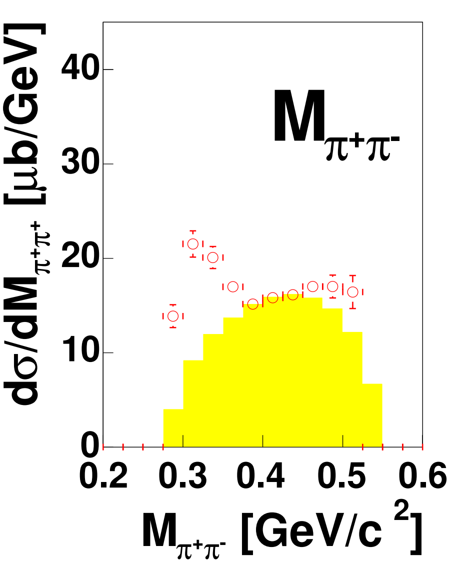

Fig. 8. The same as Fig. 7, but for the reaction $pd \to {}^3$He $\pi^+\pi^-$.

of each other (and dividing the $\pi^+\pi^-$ cross section by a factor of two in order to account for the trivial isospin factor between both channels) we see that strength starts to build up towards low masses in $M_{\pi^+\pi^-}$, but obviously cannot continue in this channel because of the $\pi^+\pi^-$ threshold. Instead, due to the 9 MeV lower $\pi^0\pi^0$ threshold, we see that the strength continues to rise towards smaller masses in the $\pi^0\pi^0$ channel.

An $I_{\pi\pi} = 1$ contribution to the $\pi^+\pi^-$ system should show up at large invariant masses, since due to Bose symmetry it is correlated to p-waves. If we compare $M_{\pi^+\pi^-}$ and $M_{\pi^0\pi^0}$ spectra (Figs. 7 and 8) at large invariant masses, we see that they nearly coincide - taking into account the isospin factor of two for the $\pi^+\pi^-$ system - which means that the $I_{\pi\pi} = 1$ contribution indeed is very small in agreement with previous findings [1, 3] in inclusive measurements.

4 Conclusions and Outlook

We have seen that the $\pi\pi$ production both between two free nucleons and the one leading to bound nuclear systems, leads to a σ-channel enhancement at low $\pi\pi$ masses. This enhancement is particular pronounced in the $\pi^0\pi^0$ channel and increases when proceeding from the case of free NN interaction to the case of bound nuclear systems in the final state. In the $\pi^+\pi^-$ channel this enhancement appears to be much weaker, in the NN case it even is not visible.

One explanation for these findings would have been the presence of Bose-Einstein correlations in case of pairs of identical bosons, as has been discussed in detail in chapter 3.2. However, both from the theoretical point of view and from the ultimative experimental test, the experimentum crucis in the $nn\pi^+\pi^+$ channel, we see that this explanation is very unlikely - if not already ruled out.

The new exclusive data show that the socalled ABC effect is more general than thought hitherto and extends even to the basic unbound NN system. Also not anticipated before is the observation that it mainly manifests itself in the $\pi^0\pi^0$ channel. $\Delta\Delta$ calculations - be it for bound [2, 10] or unbound [8] systems - predict a double-hump structure in $M_{\pi\pi}$ as an essential feature, which obviously is not supported any longer by our exclusive data.

The fact that the low-mass enhancement is much stronger in $\pi^0\pi^0$ than in $\pi^+\pi^-$ may at least partly be connected with the fact that the $\pi^0\pi^0$ threshold is lower by 9 MeV than the $\pi^+\pi^-$ threshold. In consequence - as we have pointed out in chapter 3.2 - pion loops may play an important role and lead to an enhancement in the $\pi^0\pi^0$ channel below the $\pi^+\pi^-$ threshold. However, quantitative calculations for this scenario have not yet been carried out.

Though this scenario can possibly account for the additional enhancement in the $\pi^0\pi^0$ channel, it cannot explain, why we observe so much strength at all at low masses in the σ channel. One possibility might be chiral restoration [24, 25] or other dynamic [20] effects in the nuclear medium as observed, e.g., in $\pi A \rightarrow \pi\pi X$ [26, 27] and $\gamma A \rightarrow \pi\pi X$ [28] reactions. Yet another possibility would be a resonance-like phenomenon near $\pi\pi$ threshold, which - since not observed in reactions on a single nucleon - would need to be associated with the NN system. Such a phenomenon has been noted, e.g., in Refs. [29, 30]. Also the potential observation [31–33] of a $\gamma\gamma$ line at $M_{\gamma\gamma} \approx 2m_\pi$ could point to such a situation.

Summarizing, the first exclusive data on $pp \rightarrow pp\pi^0\pi^0$, $pp \rightarrow pp\pi^+\pi^-$, $pd \rightarrow ^3He\ \pi^0\pi^0$ and $pd \rightarrow ^3He\ \pi^+\pi^-$ in the ABC region reveal a strong enhancement in the low $M_{\pi\pi}$ region - in the $\pi^0\pi^0$ channel being much larger than in the $\pi^+\pi^-$ channel. From the data we see that this enhancement is of scalar-isoscalar nature. The observed isospin breaking may possibly be associated with that present already in the pion masses and understood as a dynamical breaking due to $\pi\pi$ loops. The reason for the basic low mass enhancement remains still unclear at present. Ideas presented include medium effects due to chiral restoration or a so far unknown phenomenon associated with the NN-system.

For a complete mapping of the $\pi\pi$ production phenomena in NN-collisions a solid data base is equally important for the $\pi^+\pi^0$ and $\pi^+\pi^+$ channels as well for all $\pi\pi$ production channels in pn collisions. Part of such data have still be taken at CELSIUS-WASA and is currently being analyzed. It is hoped that data taking on this subject can continue as soon as WASA@COSY will be ready for new measurements.

Acknowledgement: We are grateful to the TSL/ISV personnel for the continued help during the course of these measurements. This work has been supported by BMBF (06TU201), DFG (Europ. Graduiertenkolleg 683), Landesforschungsschwerpunkt Baden-Württemberg and the Swedish Research Council. We also acknowledge the support from the European Community-Research Infrastructure Activity under FP6 "Structuring the European Research Area" programme (Hadron Physics, contract number RII3-CT-2004-506078).

References

[1] N. E. Booth, A. Abashian, K. M. Crowe: *Phys. Rev. Lett.* **7** (1961) 35; **6** (1960) 258; *Phys. Rev. C* **132** (1963) 2296

[2] J. C. Anjos, D. Levy, A. Santoro: *Nucl. Phys. B* **B67** (1973) 37

[3] J. Banaigs et al.: *Nucl. Phys. B* **67** (1973) 1

[4] see; e.g., R. Wurzinger et al.: *Phys. Lett. B* **445** (1999) 423; F. Plouin, P. Fleury, C. Wilkin: *Phys. Rev. Lett.* **65** (1990) 690; for a review see A. Codino and F. Plouin, LNS/Ph/94-06

[5] W. Brodowski et al.: *Phys. Rev. Lett.* **88** (2002) 192301

[6] J. Pätzold et al.: *Phys. Rev. C* **67** (2003) 052202R

[7] J. Johanson et al.: *Nucl. Phys. A* **712** (2002) 75

[8] L. Alvarez-Ruso, E. Oset, E. Hernandez: *Nucl. Phys. A* **633** (1998) 519; L Alvarez-Ruso: *PhD thesis, Univ. Valencia* 1999 and priv. comm.

[9] H. A. Clement, M. M. Kaskulov, E. A. Doroshkevich: *Int. J. Mod. Phys. A* **20** (2005) 674; M. M. Kaskulov, H. Clement: *Phys. Rev. C* **70** (2004) 014002

[10] see e.g., A. Gardestig, G. Fäldt, C. Wilkin: *Phys. Rev. C* **59** (1999) 2608; *Phys. Lett. B* **421** (1998); C. A. Mosbacher, F. Osterfeld: *nucl-th/990364*; L. Alvarez-Ruso: *Phys. Lett. B* **452** (1999) 207

[11] M.Bashkanov et al.: *nucl-ex/0508011* and submitted for publication

[12] M. Bashkanov et al.: *Proc. STORI'05 (Eds. D. Chiladze, A. Kachavara, H. Ströher), Forschungszentrum Jülich: matter and materials* **30** (2005) 129

[13] J. Zabierowski et al.: *Phys. Scripta T* **99** (2002) 159

[14] T. Skorodko et al.: *Proc. Few Body 17 (Eds. W. Glöckle, W. Tornow), Elsevier* S243 (2004)

[15] L. G. Dakhno et al.: *Sov. J. Nucl. Phys.* **37** (1983) 540

[16] F. Shimizu et al.: *Nucl. Phys. A* **386** (1982) 571

[17] for review see, e.g., D. H. Boal, C.-K. Gelbke, B. K Jennings, *Rev. Mod. Phys.* **62** (1990) 553

[18] I. Juricic et al.: *Phys. Rev. D* **39** (1989) 1

[19] V. Bernard et al.: *Nucl. Phys. A* **580** (1994) 475

[20] L. Roca, E. Oset, M. J. Vicente-Vacas: *Phys Lett. B* **541** (2002) 77

[21] M. Kotulla et al.: *Phys Lett. B* **578** (2004) 63

[22] M. Wolf et al.: *Eur. Phys. J. A* **9** (2000) 5

[23] S. Prakov et al.: *Phys. Rev. C* **69** (2004) 045202

[24] T. Hatsuda, T. Kunihiro, H. Shimizu: *Phys. Rev. Lett.* **82** (1999) 2840

[25] Z. Aouissat et al.: *Phys. Rev. C* **61** (1999) 012202R

[26] F. Bonutti et al.: *Nucl. Phys. A* **677** (2000) 213

[27] A. Starostin et al.: *Phys. Rev. Lett.* **85** (2000) 5539

[28] J. G. Messchendorp et al.: *Phys. Rev. Lett.* **89** (2002) 222302

[29] V. V. Anisovich, V. A. Nikonov: *Eur. Phys. J. A* **8** (2000) 401

[30] M. Sander, H. V. von Geramb: *Phys. Rev. C* **56** (1997) 1218

[31] M. Bashkanov et al.: *Int. J. Mod. Phys. A* **20** (2005) 554

[32] H. Clement et al.: *Int. J. Mod. Phys. A* **20** (2005) 1747

[33] M. Bashkanov et al.: *hep-ex/0406081*