ACTA UNIVERSITATIS UPSALIENSIS

*Uppsala Dissertations from
the Faculty of Science and Technology*

25

JAN JOHANSON

Two-Pion Production in Proton-Proton Collisions Near Threshold

UPPSALA 2000

Dissertation for the Degree of Doctor of Technology in Nuclear Physics presented at Uppsala University in 2000

ABSTRACT

Johanson, J. 2000: Two-Pion Production in Proton-Proton Collisions Near Threshold. Acta Universitatis Upsaliensis, *Uppsala Dissertations from the Faculty of Science and Technology* 25. 106 pp. Uppsala. ISBN 91-554-4809-7.

Two-pion production reactions in proton-proton collisions have been studied using the PROMICE/WASA detector and an internal cluster gas-jet target at the CELSIUS storage ring in Uppsala. Three out of the four isospin-independent reaction channels have been measured at several energies in the intermediate and near threshold energy region. Important parts of the analysis include the identification of neutral pions from the invariant mass of the decay gammas, the identification of positive pions with the delayed pulse technique and the use of Monte Carlo simulations to understand the detector response. The total cross sections for the $pp \rightarrow pp\pi^+\pi^-$, the $pp \rightarrow pp\pi^0\pi^0$ and the $pp \rightarrow pn\pi^+\pi^0$ reactions are presented at beam energies ranging from 650 to 775 MeV.

The production mechanism for two-pion production near threshold seems to be dominated by resonance production. The contribution from the non-resonant terms alone can not reproduce the total cross sections. In most models, two-pion production is governed by the Δ and the N^* resonances in either one or both of the participating nucleons. The $N^*(1440) \rightarrow N(\pi\pi)_{S-wave}^{T=0}$ transition has been suggested as the dominating production mechanism for two-pion production in proton-proton collisions. However, the total cross sections presented in this thesis show that other production mechanisms also must give large contributions.

*Jan Johanson, Department of Radiation Sciences,
Uppsala University, Box 535, S-751 21 Uppsala, Sweden.*

© Jan Johanson 2000

ISSN 1104-2516

ISBN 91-554-4809-7

Printed in Sweden by Gotab, Stockholm, 2000

Distributor: Uppsala University Library, Uppsala, Sweden

Till mina föräldrar

(The BBC had returned my script) "...asking whether I could let them have something more profound. I replied that I could not promise to write something more profound, but if that would be more acceptable, I could easily make it more obscure"

(Sir Vincent Wigglesworth, 1899-1994)

Contents

1	Introduction	11
2	Theory and previous experiments	13
2.1	Theoretical background	14
2.1.1	Isospin analysis	15
2.1.2	Two-pion production models	17
2.2	Previous experiments	19
3	The experimental setup	23
3.1	The CELSIUS storage ring	23
3.2	The cluster gas-jet target	25
3.3	The PROMICE/WASA detector	25
3.3.1	The forward detector	27
3.3.2	The central detector	30
3.4	The data acquisition system	32
3.5	The light pulser system	33
3.6	The trigger system	33
3.6.1	Triggers used in the experiments	35
3.7	Measurement periods	37
4	Analysis	39
4.1	The analysis programs	40
4.1.1	Phase space Monte Carlo - GIN	40
4.1.2	Simulating the detector response - WMC	40
4.1.3	Event reconstruction - PW	42
4.2	Alignment and beam energy	42
4.2.1	Alignment of the detector	43

4.2.2	Beam energy	44
4.2.3	Vertex position	45
4.3	Detector calibration	46
4.3.1	Energy calibration of the forward detector	46
4.3.2	Time calibration of the forward detector	48
4.3.3	Energy calibration of the central detector	48
4.4	Energy reconstruction	49
4.4.1	The forward detector	49
4.4.2	The central detector	50
4.5	Track reconstruction	50
4.5.1	The forward detector	51
4.5.2	The central detector	52
4.6	Particle identification	52
4.6.1	The $\Delta E_1/\Delta E_2$ method	53
4.6.2	The delayed pulse technique	57
4.7	Event selection	59
4.7.1	The $pp \rightarrow pp\pi^+\pi^-$ reaction	59
4.7.2	The $pp \rightarrow pp\pi^0\pi^0$ reaction	60
4.7.3	The $pp \rightarrow pn\pi^+\pi^0$ reaction	65
4.8	Normalization	68
4.8.1	Selection of elastic scattering events	69
4.8.2	Calculation of the integrated luminosities	71
4.9	Efficiencies and Errors	75
4.9.1	Acceptance and event reconstruction efficiency	75
4.9.2	Final state interaction	76
4.9.3	Trigger efficiencies	79
4.9.4	The efficiency of the delayed pulse technique	81
4.9.5	The efficiency of the central $\Delta E_1/\Delta E_2$ detector	82
4.9.6	Errors	84
5	Results and conclusions	87
5.1	The $pp \rightarrow pp\pi^+\pi^-$ reaction	88
5.1.1	The total cross section	88
5.1.2	Kinematical distributions	89
5.2	The $pp \rightarrow pp\pi^0\pi^0$ reaction	92
5.2.1	The total cross section	92
5.2.2	Kinematical distributions	92
5.3	The $pp \rightarrow pn\pi^+\pi^0$ reaction	95

CONTENTS	9
<hr/>	
5.3.1 The total cross section	95
5.3.2 Kinematical distributions	96
5.4 Conclusions and outlook	98
A Cross sections	99
Acknowledgements	101
References	103

CHAPTER 1

Introduction

Quantum chromodynamics (QCD) is the fundamental theory of the strong interaction. The force between the quarks is mediated by the exchange of massless spin-1 bosons, the gluons. It is however not clear how the nucleon-nucleon, nucleon-meson and meson-meson interactions are connected to the quark-quark interaction. QCD calculations work nicely in the perturbative region at high energies, but are difficult to carry out in the confinement region of hadron and nuclear physics where perturbative methods cannot be applied. The strong force between nucleons is instead described effectively by meson exchange where the characteristics of the nuclear force is given by the mass and quantum numbers of the involved exchange mesons.

Two-pion production in proton-proton collisions is one way to learn more about the nucleon-nucleon, pion-nucleon and pion-pion interactions. The high momentum transfers necessary to produce mesons in nucleon-nucleon collisions near the energy threshold offers an opportunity to study the short-range part of the nuclear force. An advantage of studying two-pion production in the near threshold energy region is that only a few partial waves contribute in the reaction processes, thus simplifying both the interpretation of the data and the theoretical calculations. However, the total cross sections are small which makes the experiments difficult to perform. The new storage ring facilities with thin internal targets have opened up new possibilities for threshold experiments. The necessary combination of high luminosities and low background can be achieved using stored circulating beams passing through thin windowless internal targets many times.

The production mechanism for two-pion production seems to be dominated by resonance production. Data in the near threshold energy region could prove to be very selective as to which resonance gives the largest contribution. The previously existing data on two-pion production reactions in proton-proton collisions near threshold are scarce, especially for the reaction channels involving one or two neutral pions in the final state. The possible two-pion production reactions in proton-proton collisions and their thresholds are listed in table 1.1. The thresholds are expressed in the kinetic energy of the proton beam.

Table 1.1. The possible two-pion production reactions in proton-proton collisions together with their thresholds expressed in the kinetic energy of the beam. The beam energies for which data are presented in this thesis are also shown together with the corresponding excess energies in the CMS (Q).

Reaction	Threshold (MeV)	Beam energies (MeV)	Q (MeV)
$pp \rightarrow pp\pi^+\pi^-$	600	650, 680	22, 35
$pp \rightarrow pp\pi^0\pi^0$	579	650, 725, 750, 775	31, 63, 74, 84
$pp \rightarrow pn\pi^+\pi^0$	592	725, 750, 775	57, 68, 78
$pp \rightarrow d\pi^+\pi^0$	587		
$pp \rightarrow nn\pi^+\pi^+$	606		

Experimental studies on two-pion production in proton-proton collisions, performed closer to threshold than ever before, are presented in this thesis. The experiments were performed using the PROMICE/WASA detector and an internal cluster gas-jet target at the CELSIUS storage ring in Uppsala. Three out of the four isospin-independent reaction channels were measured at several energies in the intermediate and near threshold energy region. The total cross sections for the two-pion production reactions $pp \rightarrow pp\pi^+\pi^-$, $pp \rightarrow pp\pi^0\pi^0$ and $pp \rightarrow pn\pi^+\pi^0$ at the beam energies shown in table 1.1 are presented. Total and differential cross sections for the reaction $pp \rightarrow pp\pi^+\pi^-$ at 725 and 750 MeV will be published in [1] and at 775 MeV in [2].

CHAPTER 2

Theory and previous experiments

Already in the 1950s it was proposed that the nuclear force could be divided into three parts, a long-range part ($r \geq 2$ fm), an attractive intermediate part ($1 \text{ fm} \leq r \leq 2 \text{ fm}$) and a strongly repulsive short-range part ($r \leq 1 \text{ fm}$) [3]. In meson theory, the different parts of the nuclear force are described by the exchange of scalar, pseudoscalar and vector mesons. The first section in this chapter starts with a short introduction to the meson theory of the strong interaction.

In the second part of the first section, the total cross sections of the isospin independent two-pion production reactions in proton-proton collisions are expressed in terms of isospin amplitudes. Four isospin amplitudes and one relative phase between two amplitudes are needed to describe the total cross sections.

In the last part of the first section, an introduction to a few models on two-pion production is given. In all models, the two-pion production is governed by the Δ and the N^* resonances in either one or both of the participating nucleons in addition to the contribution from the non-resonant terms.

A summary of the experiments on two-pion production reactions in proton-proton collisions in the intermediate and near threshold energy region performed before the PROMICE/WASA experiment is given in the second section of this chapter. All but one of the earlier experiments were performed using a bubble chamber.

2.1 Theoretical background

The long-range part of the nuclear force is explained by one-pion exchange. The pseudoscalar nature of the pion gives rise to a tensor force. A tensor force also appears from ρ exchange, although the sign is different from the tensor force created by the pion, which reduces the overall tensor strength of the nuclear potential. The short-range repulsion is explained by ω exchange. The ω meson also gives rise to a spin-orbit force. However, there is no meson available to explain the intermediate-range attraction of the nuclear force. A scalar-isoscalar meson with a mass between 500 and 700 MeV/c² could provide this. Unfortunately, no such meson has been found experimentally. Instead, the intermediate-range attraction is attributed to 2π exchange. In the one-boson exchange model (OBE), a scalar-isoscalar meson with the appropriate mass is invented, the σ meson. The approximation is motivated by the strong attraction between pions in a relative S-wave. Heavier mesons are usually omitted in the models, since their contribution would be in the short-range region of the nuclear force where quark effects are expected to dominate the interaction.

One way to improve the OBE model is to introduce 2π exchange instead of the σ meson [4]. In doing this, correlated 2π exchange must also be considered. The contribution from correlated 2π exchange is of similar size as the contribution from uncorrelated 2π exchange. Correlated 2π exchange where the pions are in a relative P-wave can be described by the exchange of the ρ meson. Correlated 2π exchange where the pions are in a relative S-wave can be approximated by the exchange of a scalar-isoscalar meson, the σ' . As opposed to the σ in the OBE model, the σ' is based on empirical evidence. The models are further improved by introducing isobars, in particular the low lying πN resonance $\Delta(1232)$. The improved models successfully describe the long- and intermediate-range part of the nucleon-nucleon interaction.

At a beam energy around 300 MeV, one-pion production becomes possible. The one-pion production up to ~ 1 GeV is dominated by the excitation of the $\Delta(1232)$ resonance. For two-pion production, and one-pion production at higher energies, other resonances start to give important contributions. The meson-exchange models can be further improved with better knowledge of the involved resonances and the size of their contributions to the production mechanism. To achieve this, more experimental data in the intermediate and near threshold energy region are needed.

2.1.1 Isospin analysis

The only difference between a proton and a neutron in the absence of the electromagnetic interaction is a small mass difference. In the isospin formalism, the proton and the neutron are considered as two different states of the same particle, the nucleon. In analogy with a spin- $\frac{1}{2}$ system, the proton and the neutron are assigned isospin $\frac{1}{2}$, with $+\frac{1}{2}$ and $-\frac{1}{2}$ for the third component of the isospin respectively. Since isospin is conserved in the strong interaction, it can be used to derive relations between the amplitudes of different reaction channels.

The reaction amplitudes of the four isospin independent two-pion production reactions in proton-proton collisions can be decomposed into different isospin amplitudes corresponding to the initial and final isospin states of the system. The initial state is completely determined by the isospin of the proton pair. The isospin of the final state can be classified by the isospin of the nucleon pair and the pion pair [5, 6]. The total cross sections for the different reaction channels can then be expressed in terms of the isospin matrix elements $M_{I_f I_{2\pi} I_i}$, where I_i denotes the initial isospin of the nucleons, I_f denotes the final isospin of the nucleons and $I_{2\pi}$ denotes the isospin of the produced pion pair. The only two amplitudes which interfere are M_{121} and M_{101} . All other cross products disappear since they are orthogonal in the NN-space and involve states with different l . Denoting the relative phase between M_{121} and M_{101} ϕ , the total cross sections for two-pion production in proton-proton collisions are:

$$\sigma(pp\pi^+\pi^-) = \frac{1}{120}|M_{121}|^2 + \frac{1}{8}|M_{111}|^2 + \frac{1}{6}|M_{101}|^2 + \frac{1}{\sqrt{180}}|M_{121}||M_{101}|\cos\phi \quad (2.1)$$

$$\sigma(pp\pi^0\pi^0) = \frac{1}{60}|M_{121}|^2 + \frac{1}{12}|M_{101}|^2 - \frac{1}{\sqrt{180}}|M_{121}||M_{101}|\cos\phi \quad (2.2)$$

$$\sigma(pn\pi^+\pi^0) = \frac{3}{40}|M_{121}|^2 + \frac{1}{8}|M_{111}|^2 + \frac{1}{4}|M_{011}|^2 \quad (2.3)$$

$$\sigma(nn\pi^+\pi^+) = \frac{3}{20}|M_{121}|^2 \quad (2.4)$$

In the expressions for the total cross sections above, a factor taking care of the number of identical particles in the final state is included for each reaction. The factor is 1 for reaction 2.3, 2 for reaction 2.1 and 4 for reactions 2.2 and 2.4. There are five unknown parameters on the right-hand

Figure 2.1. The formation of an $N^*(1440)$ and its subsequent decay into a nucleon and a pion pair.

Figure 2.2. The formation of two Δ isobars and the subsequent decay of each Δ isobar into a nucleon and a pion.

side of Eq. 2.1–Eq. 2.4, four amplitudes and the relative phase ϕ . Unfortunately, there are only four total cross sections that can be measured in Eq. 2.1–Eq. 2.4. A complete determination of the isospin amplitudes must therefore include measurements on a neutron target.

Nevertheless, a few interesting relations can be derived under certain assumptions. The total wave function of the pion pair must be symmetric since it describes a system of particles with integer spin. If the pions are in a relative S-wave, i.e. $l_{\pi\pi}=0$, the isospin of the pion pair has to be even in order for the wave function, $\Psi(2\pi)$, to be symmetric. Suppose that the production mechanism near threshold is dominated by the $N^*(1440)$ resonance, shown in Fig. 2.1. The only amplitude which gives a contribution in this case is M_{101} , which leads to the prediction that the ratios between the total cross sections for the reactions 2.1–2.4 are 2:1:0:0. If the production mechanism near threshold instead is dominated by double $\Delta(1232)$ production, shown in Fig. 2.2, the total cross sections are related in a more complicated manner. The isospin amplitudes M_{111} and M_{011} do not contribute in this case, which leads to the prediction that the total cross section of reaction 2.4 is twice that of reaction 2.3.

If the pions are in a relative P-wave, i.e. $l_{\pi\pi}=1$, the isospin of the pion pair has to be odd, which leaves only the M_{111} and M_{011} isospin amplitudes for both the $N^*(1440)$ and double $\Delta(1232)$ hypothesis. The total cross sections for the reactions 2.2 and 2.4 would then be zero and

the only difference between the total cross sections for the reactions 2.1 and 2.3 would be the contribution from the M_{011} amplitude.

2.1.2 Two-pion production models

Most of the models describing two-pion production in the intermediate and near threshold energy region come from the theory group at the university of Valencia. They have developed models for the $\gamma N \rightarrow \pi\pi N$ and $\pi N \rightarrow \pi\pi N$ reactions as well as the only existing model describing all isospin-independent reaction channels in the $NN \rightarrow \pi\pi NN$ reaction. The two former models share many features with the model for the $NN \rightarrow \pi\pi NN$ reaction and are therefore briefly described before discussing the model relevant to this thesis.

The model for the $\gamma N \rightarrow \pi\pi N$ reaction was developed by G3mes and Oset [7]. The model includes non-resonant terms as well as terms describing the $\Delta(1232)$, the $N^*(1440)$ and the $N^*(1520)$ resonances. The $\gamma N \rightarrow \Delta(1232)\pi$ transition is found to be the dominating production mechanism near threshold. The $N^*(1520)$ resonance plays an important role at somewhat higher energies due to its strong interference with the dominating production mechanism. The model gives a good description of the total cross sections for the $\gamma p \rightarrow \pi^+\pi^-p$ and the $\gamma p \rightarrow \pi^0\pi^0p$ reactions below $E_\gamma=800$ MeV. However, the model fails to reproduce the total cross section for the $\gamma p \rightarrow \pi^+\pi^0n$ reaction in the same energy region [8].

The model for the $\pi N \rightarrow \pi\pi N$ reaction was developed by Oset and Vicente-Vacas [9]. In analogy with the previous model, it includes non-resonant terms as well as terms describing the Δ and N^* resonances. The $N^*(1440)$ resonance with its subsequent decay $N^*(1440) \rightarrow N(\pi\pi)_{S-wave}^{T=0}$ was found to be very important near threshold. The model was later extended by Sossi et al. [10] to include Feynman diagrams describing the $N^*(1440) \rightarrow N(\pi\pi)_{p-wave}$ decay. The extended model describes the total cross section for the $\pi^-p \rightarrow \pi^+\pi^-n$ reaction well near threshold but fails at reproducing the total cross section for the $\pi^+p \rightarrow \pi^+\pi^+n$ reaction in the same energy region [11].

The dominating production mechanisms near threshold differ for the $\gamma N \rightarrow \pi\pi N$ and the $\pi N \rightarrow \pi\pi N$ reactions discussed above. The total cross section for the $\gamma N \rightarrow \pi\pi N$ reaction is dominated by the Δ resonance near threshold whereas the N^* resonance dominates the total cross section near threshold for the $\pi N \rightarrow \pi\pi N$ reaction.

Alvarez-Ruso, Oset and Hernández have developed a model for the $NN \rightarrow \pi\pi NN$ reaction which is valid from threshold up to a kinetic energy of 1400 MeV of the incoming proton [12]. The model is inspired by the earlier models on two-pion production discussed above, in particular the model for the $\pi N \rightarrow \pi\pi N$ reaction, where the $N^*(1440)$ resonance turned out to be important near threshold. A new ingredient, as compared to two-pion production in the previous models, is the $NN \rightarrow NN^*$ transition. The model for the $NN \rightarrow \pi\pi NN$ reaction includes non-resonant production together with 12 Feynman diagrams describing the $\Delta(1232)$ and the $N^*(1440)$ resonances. The strength of the $NN \rightarrow NN^*$ transition is extracted from an experiment on the $(\alpha) \rightarrow (\alpha')$ reaction [13]. In the model, it is found that the $N^*(1440)$ resonance dominates the total cross section near threshold ($T_p \leq 800$ MeV) whenever it is allowed by isospin conservation. This is despite the fact that the $N^*(1440)$ couples weaker to the πN system than the Δ . The importance of $N^*(1440)$ comes from the decay channel $N^*(1440) \rightarrow N(\pi\pi)_{S=0}^{T=0}$. At higher energies ($T_p \geq 1000$ MeV), terms involving $\Delta(1232)$ excitation, in particular double $\Delta(1232)$ excitation, dominate the total cross section. The contributions from the non-resonant terms to the total cross section are found to be very small for most of the reaction channels.

The predictions of the model for the total cross section of the three two-pion reactions in proton-proton collisions studied in this thesis are of particular interest. In the model, the production mechanism for the $pp \rightarrow pp\pi^+\pi^-$ reaction near threshold is completely dominated by the $N^*(1440) \rightarrow N(\pi\pi)_{S=0}^{T=0}$ transition. The contribution from terms exciting Δ :s are important at higher energies whereas the contribution from non-resonant production is very small. The same is also valid for the $pp \rightarrow pp\pi^0\pi^0$ reaction. For the $pp \rightarrow pn\pi^+\pi^0$ reaction however, the production mechanism that was dominant in the two previous reactions is now forbidden by isospin conservation. Instead, non-resonant terms dominate the behaviour of the total cross section near threshold. For this reason, the model predicts that the total cross section for the $pp \rightarrow pn\pi^+\pi^0$ reaction is much smaller than the total cross sections for the $pp \rightarrow pp\pi^+\pi^-$ and the $pp \rightarrow pp\pi^0\pi^0$ reactions near threshold. The theoretical predictions of the total cross sections for the three two-pion production reactions studied in this thesis are shown in Fig. 2.3 [14].

The two theoretical predictions shown in Fig. 2.3 for each reaction channel studied in this thesis correspond to two different solutions of the

model. The Lagrangian for the $N^*(1440) \rightarrow N(\pi\pi)_{S-wave}^{T=0}$ decay channel contains two terms. The two parameters describing the contribution from each term cannot be extracted from the partial decay width alone, but must be fitted to experimental data. However, the possible values depend on each other and only two sets of parameters agree with data. The two solutions are further discussed in the article by Alvarez-Ruso, Oset and Hernández [12]. For the $pp \rightarrow pp\pi^+\pi^-$ and the $pp \rightarrow pp\pi^0\pi^0$ reactions, the two solutions differ by about a factor of two near threshold and by about 30 percent at $T_p \sim 1000$ MeV. This gives a hint of the theoretical uncertainties of the model. Final state interaction between the nucleons is not included in the theoretical predictions shown in Fig. 2.3. However, in the thesis by L. Alvarez-Ruso [15], the effects of final state interaction between the protons for the $pp \rightarrow pp\pi^+\pi^-$ reaction are discussed. It is found that including final state interaction in the model increases the total cross section by almost a factor of 10 close to threshold and by a factor of ~ 2 at $T_p = 900$ MeV.

2.2 Previous experiments

Data on two-pion production in nucleon-nucleon collisions are scarce in the energy region near threshold, especially for the reactions with one or two neutral particles in the final state. A summary of the experimental data on the four isospin-independent two-pion production reactions in proton-proton collisions in the intermediate and near threshold energy region existing before the PROMICE/WASA experiment is shown in Fig. 2.3.

Shimizu et al. [16] have measured total cross sections for all elastic and inelastic reactions in proton-proton collisions at 11 beam energies ranging from 325 to 1262 MeV. The experiment was performed using a liquid-hydrogen bubble chamber. 2-prong and, when energetically possible, 4-prong events were searched for when scanning the ~ 50000 pictures obtained at each energy. The different reactions channels were separated by χ^2 -fitting and, if more than one fit was acceptable, the bubble densities of the tracks. In addition, the positive pions were identified from their decay. All 4-prong events where the four measured particles appeared to be two protons and two pions were treated as $pp \rightarrow pp\pi^+\pi^-$ events. The 2-prong events were sorted into event categories depending on the detected particles. If the two measured particles appeared to be protons

Figure 2.3. A summary of the experimental data on the four isospin independent two-pion production reactions in proton-proton collisions in the intermediate and near threshold energy region existing before the PROMICE/WASA experiment. The theoretical predictions from the model by Alvarez-Ruso, Oset and Hernández are also shown for the three two-pion production reactions studied in this thesis.

and the missing mass of the two particles was above the mass of two neutral pions, the event was treated as a $pp \rightarrow pp\pi^0\pi^0$ event. If the two measured particles appeared to be positive pions and the missing mass of the two particles was above the mass of two neutrons, the event was treated as a $pp \rightarrow nn\pi^+\pi^+$ event. Finally, if the two measured particles appeared to be a proton and a positive pion and the missing mass of the two particles was above the summed mass of a neutron and a neutral pion, the event was treated as a $pp \rightarrow pn\pi^+\pi^0$ event. The $pp \rightarrow pp\pi^+\pi^-$ events were completely reconstructed in the analysis. The events from the other isospin independent two-pion production reactions could not be completely reconstructed in the analysis, since only two final state particles were measured for these reactions. Note that the total cross section for the $pp \rightarrow pp\pi^+\pi^-$ reaction at 767 MeV is only an upper limit.

Dakhno et al. [5] have measured total cross sections for two-pion production reactions in proton-deuteron collisions at five beam energies ranging from 730 to 978 MeV. The experiment was performed using a bubble chamber filled with deuterium. 3-prong and 4-prong events with one negative track were searched for when scanning the ~ 40000 pictures obtained at each energy. 3-prong events corresponded to events where one of the protons had a momentum below 80 MeV/c, which could not be detected in the bubble chamber. The events were identified by χ^2 -fitting and the bubble densities of the tracks. The reactions $pp(n) \rightarrow pp(n)\pi^+\pi^-$ and $pn(p) \rightarrow pn(p)\pi^+\pi^-$ were separated by assuming the nucleon with the lowest momentum in the laboratory system to be a spectator nucleon. The Fermi motion of the nucleons in the deuterium target was neglected in the analysis. It has later been estimated that the Fermi motion can shift the effective beam energy by ~ 50 MeV [17].

Cverna et al. [18] have measured total cross sections for one- and two-pion production reactions in proton-proton collisions at a beam energy of 800 MeV. A magnetic spectrometer was used to measure the momentum spectra of the emitted π^+ and π^- in the angular range $\theta=16.5^\circ$ - 60° . The $pp \rightarrow pp\pi^+\pi^-$ reaction was identified from the assumption that all negative pions must come from that reaction. There was however an excess of events in the high-momentum region of the identified negative pions. One source of background was identified as protons from elastic scattering and this background was subtracted in the analysis. An equal yield of the same shape was assumed to originate from one-pion production and therefore the background identified as coming from elastic scattering

was subtracted once more. The luminosity was extracted from the beam current and a real-time clock measuring the dead time. This method is sensitive to variations in the beam current and later experiments showed that the beam intensity did vary significantly. Comparing the measured differential cross section for elastically scattered protons with published cross sections led to a correction factor of 2 for the dead time.

Brunt et al. [19] have measured total cross sections for inelastic reactions in proton-deuteron collisions at two beam energies, 1113 and 1370 MeV. The experiment was performed using a bubble chamber filled with deuterium. 3-prong events with no obvious π^+ -tracks and 4-prong events which had one proton with momentum less than 400 MeV/c were searched for when scanning the ~ 28000 pictures obtained at each energy. The different reaction channels were identified by χ^2 -fitting and the bubble densities of the tracks. The reactions $pp(n) \rightarrow pp(n)\pi^+\pi^-$ and $pn(p) \rightarrow pn(p)\pi^+\pi^-$ were separated by assuming the nucleon with the lowest momentum in the laboratory system to be a spectator nucleon.

CHAPTER 3

The experimental setup

The experiments presented in this thesis were performed at the national Swedish facility for accelerator based research, the The Svedberg Laboratory (TSL) [20] in Uppsala. Two accelerators are in operation, the Gustaf Werner cyclotron and the CELSIUS storage and cooler ring. The ion source and the cyclotron can deliver ion beams ranging from proton beams up to highly charged xenon beams. The ion beams are used by several different experiments in physics, biology and medicine.

This chapter gives an overview of the experimental facilities which were used to collect the data analysed in this thesis. The first three sections describe the CELSIUS storage ring, the internal cluster gas-jet target and the PROMICE/WASA detector. The following three sections describe the data acquisition system, the light pulser system and the trigger system. The most important parameters for each of the five run periods where data used in this thesis were collected are summarized in the last section of this chapter.

3.1 The CELSIUS storage ring

Light ion beams from protons up to Ar^{40} can be stored, cooled and accelerated in CELSIUS [21]. The maximum kinetic energy for protons is 1360 MeV. The ring consists of four 90° bends and four straight sections. One straight section is used for injection. The next straight section contains a hydrogen pellet target [22] used by the CELSIUS/WASA collaboration. The following straight section is used for electron cooling and accelera-

Figure 3.1. A top view of the CELSIUS storage ring.

tion. The last straight section contains the cluster gas-jet target used in the experiments described in this thesis. A top view of the CELSIUS ring is shown in Fig. 3.1.

The CELSIUS ring is operated in cycles which typically last 5 to 15 minutes. In the beginning of a cycle, ions from the cyclotron are injected into the ring. The preferred method is stripping injection in which H_2^+ -ions are stripped off their electrons using a carbon foil mounted in the first bend after injection. Approximately $1.1 \cdot 10^{11}$ protons can be stored in the ring with this technique. Next in the cycle, the ions are accelerated using a rf cavity with an electric field which oscillates with the same frequency as the revolution frequency of the ions stored in the ring. The magnetic fields of the magnets are slowly increased to compensate for the increasing beam energy. The data are usually collected during the constant field part

of the cycle where the beam energy is constant. At the end of the cycle, the magnetic fields of the magnets are returned to the injection values. The duty factor, i.e. the time data can be collected, is about 80 percent with a 5 minutes cycle if electron cooling is not used.

The electron cooler compensates for the energy loss and emittance blow-up of the beam due to its interaction with the internal targets. The electron cooler can only be used for beam energies up to 550 MeV/nucleon. It is therefore not used in any of the experiments described in this thesis.

3.2 The cluster gas-jet target

A number of target beams can be produced with the cluster gas-jet target [23]. The clusters are formed by pressing the gas through a cooled nozzle at temperature and pressure conditions close to phase transition conditions between a gas and a liquid. The size of the target beam at the interaction region is determined by a skimmer. After passing the scattering chamber, the gas is collected in a cryogenic beam dump and expensive gases can be recirculated via a cleaning system. The target beam is usually blocked during injection and acceleration.

A new scattering chamber was installed during the autumn 1995. The forward part was kept from the previous scattering chamber whereas the central part changed from a cylinder to a more complex shape which allowed for new types of experiments to be performed using the cluster gas-jet target. The new central chamber can accomodate internal detectors and it is equipped with large ports on which different flanges can be mounted. The geometrical acceptance of the PROMICE/WASA experiment was not influenced by the change of the central scattering chamber.

3.3 The PROMICE/WASA detector

The PROMICE/WASA detector [24] was designed to measure meson production in the near threshold energy region. It has previously been used to study e.g. the $pp \rightarrow pp\pi^0$ [25], $pp \rightarrow pp\eta$ [26, 27] and $pn \rightarrow pn\eta/d\eta$ [28] reactions close to threshold. The charged outgoing particles, which tend to have small scattering angles close to threshold, are measured in the forward part (FD) of the detector. The neutral mesons are measured by their decay into two γ 's in the central part (CD) of the detector. A top

Figure 3.2. A top view of the PROMICE/WASA detector. Note that it is the old cylindrical scattering chamber which is shown in the figure.

Figure 3.3. A front view of one of the two installed coordinate modules from the tracker.

view of the detector is shown in Fig. 3.2.

3.3.1 The forward detector

The FD consists of window counters for triggering purposes (FWC), a tracker used to get good track resolution (FPC), a forward hodoscope used for triggering purposes and particle identification in the analysis (FHD), a forward range hodoscope used to identify particles and measure their kinetic energy in the analysis (FRH) and a forward veto hodoscope to veto against particles penetrating the FRH (FVH).

The tracker

The tracker consists of parallel layers of thin walled individual drift tubes operated in the proportional region. A coordinate module consists of four layers of drift tubes. The complete detector consists of four coordinate modules, where each module following the first one is rotated 45 degrees

Figure 3.4. A side view (left) and a front view (right) of the forward hodoscope detector. The figure shows the hit pattern from two charged particles passing through the FHD.

with respect to the preceding module. The information from all coordinate modules makes it possible to reconstruct tracks without an external reference point, such as an assumed vertex position. Only two coordinate modules rotated 90 degrees with respect to each other were installed and used in the experiments performed between 1994 and 1999. The track reconstruction in the analysis is therefore based on the position information from the tracker and an assumed vertex position. A front view of one of the two installed coordinate modules is shown in Fig. 3.3.

The forward hodoscope

The FHD consists of three layers of 5 mm thick plastic scintillators. The first and second layers are made up of 24 spirally shaped elements, twisted in opposite directions. The third layer is made up of 48 straight elements, where two elements exactly cover one element of the FRH. The structure of the three layers of the FHD makes it possible to obtain information on the scattering angle and the azimuthal angle for a hit in the detector. The FHD can be divided into 1104 pixels with a resolution of approximately 1 degree in scattering angle and 4 degrees in azimuthal angle. The hit information from the FHD is used in many triggers since it provides a fast,

though crude, online track reconstruction. Fig. 3.4 shows the hit pattern from two charged particles passing through the FHD. In the analysis, the position information from the FHD is used to put additional constraints on the position information from the tracker in the track reconstruction. The third layer of the FHD is also used in the $\Delta E_1/\Delta E_2$ method together with the FRH to identify charged particles. Each element of the third layer of the FHD is connected to multi-hit TDCs that accept up to 16 hits within a time span of 6 μ s. Positive pions are identified by detecting the delayed pulses caused by the particles from the decay of the pions. Particles entering the detector during the 6 μ s time span of the multi-hit TDCs can be misidentified as delayed pulses. The third layer of the FHD is therefore used as a veto plane to remove delayed hits in the analysis that come from the scattering chamber rather than from the FRH.

The forward range hodoscope

The FRH consists of four layers of 11 cm thick plastic scintillators where each layer has 24 elements. The FRH is used in the analysis to identify charged particles with the $\Delta E_1/\Delta E_2$ method together with the FHD, and to measure the kinetic energy of the particles that stop in the FRH. The FRH is also used in the analysis to identify positive pions with the delayed pulse technique together with the FHD. Each element of the FRH is connected to multi-hit TDCs of the same type as those connected to each element in the third layer of the FHD. The delayed pulse technique, which proved to be a very important tool in the analysis, is further described in section 4.6.2. A front view of the FRH is shown in Fig. 3.5.

The forward veto hodoscope

The FVH consists of 12 horizontally arranged plastic scintillator bars. Each bar is 20 mm thick, 137 mm wide and 1650 mm long. The bars are read out by photo-multiplier tubes on both ends which makes it possible to obtain horizontal hit information from the time difference with a hit resolution of approximately 12 cm. The FVH is used in triggers as well as in the analysis to veto particles that pass through the FRH. In the analysis, it is necessary to know if the particle stopped in the FRH to allow for an unambiguous energy determination. A front view of the FVH is shown in Fig. 3.6.

Figure 3.5. A front view of the forward range hodoscope.

Figure 3.6. A front view of the forward veto hodoscope.

3.3.2 The central detector

The central detector from the PROMICE/WASA setup was partly dismantled during the autumn 1997 and completely dismantled during the spring 1998. The main purpose of the CD was to measure gammas from the decay of neutral mesons. The CD consisted of a central electromagnetic calorimeter (CEC) which, in turn, consisted of two boxes with CsI crystal arrays mounted on each side of the scattering chamber. $\Delta E_1/\Delta E_2$ detectors were mounted in front of each box to detect charged particles. Upstream veto detectors were mounted on each side of the scattering chamber, but they were never used in the analysis presented in this thesis.

The CsI boxes

Each box contained 7×8 CsI(Na) 30 cm long crystals. The geometrical coverage of the CsI boxes was almost 60 degrees in scattering angle and ± 25 degrees in azimuthal angle. The boxes were mounted on rails surrounding the target and could be moved to cover different angular regions in polar angle. The minimum scattering angle which could be covered by the CsI boxes was 30 degrees. The CsI boxes were included in the main trigger to select events with neutral pions in the final state together with the central $\Delta E_1/\Delta E_2$ detector. In the analysis, the information from the

Figure 3.7. A front view of one of the CsI boxes (above) and one of the crystals in the box (below).

Figure 3.8. A front view of the central $\Delta E_1/\Delta E_2$ detector used from the April 1996 run and onwards.

CsI boxes were used to measure the energies and positions of the detected gammas. Fig. 3.7 shows a front view of a CsI box (above) and one of the crystals in the box (below).

The central $\Delta E_1/\Delta E_2$ detector

The central $\Delta E_1/\Delta E_2$ detector was used to determine if a CD track was neutral or charged. In March 1995 it consisted of 8 vertical plastic scintillator bars mounted in front of each CsI box (CDE). Each bar was 8 mm thick. From the April 1996 run and onwards, a new central $\Delta E_1/\Delta E_2$ detector was installed (CFB) with improved angular resolution for charged particles. The CFB consisted of 4.5 mm thick plastic scintillators with 20 elements mounted in the horizontal direction and 28 elements mounted in the vertical direction in front of each CsI box. The central $\Delta E_1/\Delta E_2$ detector was included in the trigger used to select the events with neutral pions in the final state. In the analysis, the central $\Delta E_1/\Delta E_2$ detector was used to identify elastically scattered protons together with the FD. Fig. 3.8 shows a front view of the CFB detector.

Figure 3.9. The layout of the data acquisition system.

3.4 The data acquisition system

The PROMICE/WASA setup comprises approximately 450 channels connected to ADCs and 1500 channels connected to TDCs. The analog signals from the detectors are transmitted to the counting room via 43 m long BNC cables. The signals from the plastic scintillators and the CsI crystals are split in two parts. One part is fed to discriminators to be used in triggers and for time measurements. The other part is fed via a delay line to charge sensitive ADCs for energy measurements.

The data acquisition system (DAS) used in the PROMICE/WASA experiment is built around the VALET-Plus VME-based system developed at CERN [29, 30]. The data are transferred from FASTBUS and CAMAC front-end-electronics to a VALET processor via VME interfaces. The processor performs the data acquisition and writes the data to Exabyte tapes for analysis. The DAS can process up to 500 kBytes/second with a system busy time of about 50 percent. Usually the total trigger rate is reduced to give a dead time of around 40 percent for the DAS,

which corresponds to approximately 350 recorded events per second. The layout of the data acquisition system is shown in Fig. 3.9.

A link between the FASTBUS and the VME is integrated in the VALET system. It consists of a buffer memory located in the VALET crate and a FASTBUS smart card controller (FSCC) [31]. When the FSCC receives a master trigger signal, the ADC and TDC data are read out and the information is stored in an internal memory. When all channels are read out, the memory is emptied via a link to the pedestal suppression interface (PSI) in the VALET crate and the FSCC processor returns to an idle state. The PSI contains a pedestal memory which makes it possible to suppress data below predefined pedestal values. This greatly increases the acquisition capacity of the VALET system.

Two PCs were connected in parallel to the FASTBUS-VME link, one was used for online monitoring of the detectors and one was used for online event reconstruction. At the beginning of the run in April 1997, the VALET processor broke down. The processor was replaced by a PowerPC running under Windows NT.

3.5 The light pulser system

The stability of the scintillator detectors and the electronics used to read out the scintillator detectors is monitored with a light pulser system [32]. A pulse generator activates three high-voltage pulsers for the FRH, the FHD and the CEC respectively. The high-voltage pulsers are, in turn, connected to light-emitting diodes (LEDs) which feed each element of the FHD, the FRH and the CEC with light flashes via optical fibers. The light outputs of the LEDs are similar to what is expected from particles detected in the experiment. Each LED is connected to a photodiode which makes it possible to monitor the stability of the LEDs as well.

3.6 The trigger system

The total signal rate in the experiments is of the order of 10^5 per second whereas the DAS only can process about 350 events per second. The trigger system is used to reduce the signal rate and select the interesting events that should be processed by the DAS. All signals from the scintillator detectors can be included in primary and secondary triggers. The

Figure 3.10. The layout of the trigger system.

primary triggers put simple conditions on separate detectors e.g. conditions on hit multiplicity or minimum number of hit planes. The secondary triggers are formed by combining primary triggers in programmable logic units. A logic decision is made within 100 ns and a special trigger unit activates the DAS and generates gate signals to the ADCs and stop signals to the TDCs. The ADC time gates are 200 ns for the plastic scintillators and $2\mu\text{s}$ for the CsI crystals. Up to 13 different triggers can be connected to the DAS. High-rate triggers can be prescaled in factors of 2^n , where n is an integer number. The logic trigger signals are connected to TDCs, which makes it possible to check offline which trigger activated the DAS. The triggers are also connected to scalers which are used online to monitor the trigger rates and offline to check the prescaling factor for prescaled triggers. The layout of the trigger system is shown in Fig. 3.10.

Several different kinds of triggers are used in the experiments. The physics triggers are used to pick out the possible $pp \rightarrow pp\pi^+\pi^-$, $pp \rightarrow pp\pi^0\pi^0$

and $pp \rightarrow pn\pi^+\pi^0$ events. In addition, triggers to pick out elastically scattered protons for calibration and normalization purposes are connected. The simple primary triggers which make up the more complicated secondary triggers are also connected to allow for a systematic efficiency check of the physics triggers. A trigger from the light pulser is connected to monitor the stability of the detector response.

3.6.1 Triggers used in the experiments

Three main types of triggers were used in the experiments to pick out the interesting events. Triggers that pick out events with three FD charged tracks for the $pp \rightarrow pp\pi^+\pi^-$ reaction, triggers that pick out events with at least two CD neutral tracks for the $pp \rightarrow pp\pi^0\pi^0/pn\pi^+\pi^0$ reactions and triggers that pick out events with one FD charged track for the $pp \rightarrow pp$ reaction. The efficiencies of the various triggers are discussed in section 4.9.3. The primary triggers that were combined into the secondary triggers used in the experiments are described in table 3.1.

Table 3.1. The primary triggers used to form secondary triggers.

Trigger	Description
W2	Two hits in FWC
FVH	Veto from FVH, 100 ns inverted
TJ1	Three hits in the first plane of the FHD
TJ2	Three hits in the second plane of the FHD
TJ3	Three hits in the third plane of the FHD
TR3	Three hits in the first plane of the FRH
T8	One hit in CEC left and one hit in CEC right
T5	One CDE plane hit (valid for March 1995)
V5	Veto from T5, 500 ns inverted (valid for March 1995)
V5°	As V5 but with updated timing (valid for March 1995)

Triggers to pick out $pp \rightarrow pp\pi^+\pi^-$ events

It is necessary to identify at least three of the four outgoing particles from the $pp \rightarrow pp\pi^+\pi^-$ reaction to be able to identify the events and make a complete event reconstruction in the analysis. The triggers were therefore

designed to pick out events with at least three charged tracks in the FD. A few different triggers were tried, but in the end only two were used. For all runs except September 1996, the main trigger was TWR32. TWR32 was a secondary trigger defined as a logic AND of the primary triggers W2, TJ3 and TR3. In the middle of the April 1996 run, the trigger TWR32 was changed by mistake to include TJ1 instead of TJ3. However, this did not change the efficiency of the trigger by more than one percent. In September 1996, it was believed that the efficiency of the third plane of the FHD was lower than the efficiencies of the first and second planes of the FHD. As a consequence, the main trigger was changed from TWR32 to TWJ12. TWJ12 was defined as a logic AND of the primary triggers W2, TJ1 and TJ2. The rates of TWR32 and TWJ12 varied significantly with the beam intensity, but were usually $\sim 10^2$ Hz.

Triggers to pick out $pp \rightarrow pp\pi^0\pi^0$ and $pp \rightarrow pn\pi^+\pi^0$ events

The neutral pions from the $pp \rightarrow pp\pi^0\pi^0/pn\pi^+\pi^0$ events decay at the interaction vertex. The two gammas from the decay can be detected in the CD. The triggers to pick out these events were designed to be set for events with one gamma in each CsI box. In March 1995, the main trigger was T14 [28]. T14 was a secondary trigger defined as a logic AND of the primary triggers T8, V5 and V5°. Only the inner crystals of each CsI box were included in the trigger. A gamma with its main energy deposition in an outer crystal would be discarded in the analysis anyway since some of its energy may have leaked out of the detector. The inner crystals in both CsI boxes were summed in groups consisting of two or four crystals each to reduce the number of electronic channels.

Since the CDE detector was replaced by the CFB detector in April 1996, a new trigger to pick out events with one gamma in each CsI box was defined, T10. T10 was a primary trigger which was set for events with hits in the inner crystals of both CsI boxes and no hits in any of the CFB planes. The veto times of the CFB planes were 500 ns. T10 was similar to the former T14 trigger but due to timing problems, the efficiency of the new trigger was considerably lower as compared to the efficiency of T14. In April 1996 and April 1997, T10 was connected to a prescaler TDC even though it was not prescaled. This improved the efficiency of T10 as the prescaler TDC was less sensitive to bad timing than the normal trigger TDC. In September 1996, T10 was only connected to the normal TDC.

The rates of T14 and T10 varied to some extent with the beam intensity, but were usually ~ 10 Hz.

Triggers to pick out $pp \rightarrow pp$ events

The triggers to pick out elastically scattered protons can either be designed to look for one charged track in the CD or one charged track in the FD. The two primary triggers that were used in the experiments described in this thesis both picked out events with one charged track in the FD. T3 was defined as one hit in the first plane of the FRH and T1 was defined as at least one element hit in two planes of the FHD. T3 was used as the main trigger in all runs except March 1995. In March 1995, T3 was not connected until the middle of the run at 725 MeV and T1 had to be used instead. Both T3 and T1 had triggers rates of the order of 10^5 Hz and were therefore prescaled in the experiments.

3.7 Measurement periods

The data used in this thesis were collected in March 1995, April 1996, September 1996, April 1997 and March 1998. In total $\sim 400 \cdot 10^6$ events were recorded on 96 EXABYTE tapes. Several experiments using different ion beams, beam energies and target beams were usually performed during a run period. Each run period started with a calibration run which was used offline to calibrate the detector and online to check that the detector was working. For all runs used in this thesis, except during the September 1996 run, the accelerator cycle time was 300 seconds with a duty factor of ~ 80 percent. In September 1996 the cycle time was instead 900 seconds with a duty factor of ~ 93 percent. A summary of all runs used in this thesis is given in table 3.2. The time allocated for a certain experiment is expressed in 8-hour shifts.

The new DAS, installed at the beginning of the run in April 1997, could handle a higher event rate than the old DAS. This made it possible to run at a higher beam intensity during the April 1997 and March 1998 runs, as compared to the previous runs.

Before the run in March 1998, the crystals in the CsI boxes had been moved to the new CELSIUS/WASA setup and, as a result, the $pp \rightarrow pp\pi^0\pi^0/pn\pi^+\pi^0$ reactions could not be studied at 680 MeV. The CFB detector planes were mounted on the empty CsI boxes to allow for

Table 3.2. A summary of all runs used in this thesis.

Run	T_p (MeV)	Shifts	I_{av}^{beam} (mA)	Tapes	Events
Mar95	725	5	5.8	8	$35.7 \cdot 10^6$
Mar95	750	4	6.2	5	$26.6 \cdot 10^6$
Apr96	650	7	7.6	11	$43.8 \cdot 10^6$
Apr96	750	20	6.8	25	$107.6 \cdot 10^6$
Apr96	775	8	8.1	11	$45.8 \cdot 10^6$
Sep96	650	10	6.7	17	$51.3 \cdot 10^6$
Apr97	650	15	12.5	6	$48.4 \cdot 10^6$
Mar98	680	11	20.5	13	$40.6 \cdot 10^6$

the detection of charged particles in the CD.

In addition to the runs mentioned above, a run in September 1997 was performed. The main purpose of this run was to fine tune the π^+ calibration of the FD and to measure the efficiency of the delayed pulse technique using events from the $pp \rightarrow pn\pi^+$ and $pp \rightarrow d\pi^+$ reactions at three different beam energies, 360, 400 and 425 MeV. One tape of data was collected at 580 MeV, which is below the threshold for two-pion production in proton-proton collisions. This tape was used in the analysis to check the background conditions for the two-pion production reactions.

In both the March 1998 and September 1997 runs, an internal detector was mounted on the left side of the scattering chamber to allow for the detection of spectator nucleons in the reactions $pd \rightarrow pd\pi^0/ppn\pi^0$. The detector covered scattering angles between 62 and 90 degrees. The internal detector covered partly the same angular region where elastically scattered protons were detected. For this reason, only the right side of the CD was used when normalizing the data from the March 1998 run.

CHAPTER 4

Analysis

The goal of the analysis is to extract the total cross sections for the two-pion production reactions in proton-proton collisions from the experimental data. This task is a major part of the experimental work. It includes, among other things, understanding the detector response, identifying the recorded events and finding the efficiency of the various steps in the event reconstruction. The first section in this chapter describes the programs that are used at the different stages of the analysis.

The alignment, i.e. the exact position of the detector, the vertex position and the beam energy must be known for each run. Furthermore, calibration constants used to translate the ADC information to kinetic energy and the TDC information to time must be extracted. Sections 4.2 and 4.3 describe how the alignment is checked in the analysis and how the calibration constants are extracted using a special calibration run.

When the alignment and the calibration constants are known, the events on tape can be reconstructed. This includes track reconstruction, energy reconstruction and particle identification. The reconstructed events are sorted into event categories as possible $pp \rightarrow pp\pi^+\pi^-$, $pp \rightarrow pp\pi^0\pi^0$ or $pp \rightarrow pn\pi^+\pi^0$ events. The final event identification is performed in separate programs. Sections 4.4 - 4.7 describe these steps in detail.

The reactions are normalized using elastically scattered protons recorded in parallel. The partial-wave analyses of the world data on NN-elastic scattering from the SAID data base are used as reference data. The normalization procedure and the integrated luminosities for the different run periods are presented in section 4.8.

The efficiencies and the associated errors of the different steps in the

event reconstruction must be known to be able to calculate the experimental total cross sections. Monte Carlo simulations as well as other methods to study efficiencies are described in section 4.9. The general outline of the analysis is shown in Fig. 4.1.

4.1 The analysis programs

The PROMICE/WASA Offline Program Library [33] provides the basic tools necessary to decode and analyse the data from the experiments. It is written in FORTRAN 77 and uses standard packages from CERNLIB [34] together with routines specific for the PROMICE/WASA experiment. A number of subroutines have been added to the previously existing code in order to analyse the reactions studied in this thesis.

4.1.1 Phase space Monte Carlo - GIN

The GIN program is an interface to the FOWL [35] program which generates events according to phase space. It is possible to modify phase space by adding a weight factor to each event. In this way, a resonance or final state interaction between any set of the outgoing particles can be simulated. GIN can be used to study the detection acceptance of the detector setup for various reactions or as an event generator for the next step in the Monte Carlo chain which is the simulation of the detector response.

4.1.2 Simulating the detector response - WMC

The detector response is simulated using the program package GEANT-[36]. The WMC program is the PROMICE/WASA interface to the package. In GEANT, the detector is described as a set of geometrical volumes which can be passive or active. Passive volumes are detector structures which influence the tracks but do not give any information in the experiment. Passive volumes can e.g. be the beam pipe or the scattering chamber. Active volumes are associated with specific materials which give ADC and TDC information in the experiment, e.g. the scintillators in the FD. The WMC takes the detector geometry from an alignment file and events generated in FOWL as input. The particles are tracked through the detector in small steps. In each step, the particles interactions

Figure 4.1. A flow diagram of the event reconstruction and the programs that are used at the different stages of the analysis.

with the surrounding material are simulated using parameterizations of known cross sections. The output data are saved on a similar format as real data which makes it possible to run the same analysis routines on real and Monte Carlo generated events.

4.1.3 Event reconstruction - PW

Both real and Monte Carlo generated events are decoded and reconstructed in the PW program as described in sections 4.4 - 4.7. The run-specific information needed to reconstruct the events is stored in special alignment files. These files contain e.g. the present detector set-up with the exact positions of the individual detectors, the vertex position, the beam energy and the calibration constants.

The digitalized raw data from the experiments are decoded using the program EPIO [37]. Most of the $\sim 400 \cdot 10^6$ events stored on EXABYTE tapes from the experiments are not interesting in the physics analysis and a two-step filtering process is performed to reduce the data set. In the first step, events are selected using the hardware triggers and a requirement on minimum number of reconstructed tracks. The remaining events are stored on disk to allow for fast access later in the analysis chain. The first step reduces the data set by a factor of 10. In the second step, a full event reconstruction is performed including track reconstruction, particle identification and energy reconstruction. Events fulfilling requirements on minimum number of identified particles are stored in HBOOK Ntuples [38]. Ntuples are two-dimensional arrays where the information is stored on an event-by-event basis. The second step again reduces the data set by a factor of 10. All in all, only ~ 1 percent of the original data remain in the physics analysis. The physics analysis is performed on the Ntuples in separate FORTRAN programs for each reaction channel. The histograms which are filled at the different stages in the analysis are studied using the program PAW++ [39].

4.2 Alignment and beam energy

The positions of the detectors and the scattering chamber were measured when the PROMICE/WASA setup was mounted in the experimental hall. It was however necessary to check the alignment in detail for each run since the experimental conditions changed from run to run and since parts

of the detector often were dismantled between the runs. The nominal beam energy is calculated from the rf frequency used to accelerate the beam and the design value of the circumference of the CELSIUS ring. The exact circumference is however not known and the nominal beam energy is therefore checked in the analysis.

4.2.1 Alignment of the detector

The detector alignment is checked in the analysis using elastically scattered protons. Events with one proton detected in the FD and one proton detected in the CD are selected. For a given alignment, the angular distributions obtained from real data are compared to those obtained from Monte Carlo data. The detectors are moved until a good agreement between real data and Monte Carlo data is achieved.

The tracker is the best aligned detector in the FD. The position of the tracker is known within a few millimeters from measurements in the experimental hall. The positions of the other detectors in the FD are determined with respect to the tracker in the analysis. A larger part of the FD was dismantled between the September 1996 run and the April 1997 run to make room for a CHICSi experiment on pion production in heavy ion collisions [40]. No significant deviations from the design positions of the FD could be found before the detector was dismantled nor after the detector had been mounted again.

Table 4.1. The positions of the CFB detector during the different run periods.

Run period	CFB right θ (degrees)	CFB right ϕ (degrees)	CFB left θ (degrees)	CFB left ϕ (degrees)
APR96	62.4	178.8	61.6	1.1
SEP96	62.3	178.7	61.4	1.0
APR97	61.6	177.4	61.4	1.9
MAR98	60.8	178.7	61.4	2.5

The position of the CD had to be checked more carefully as it was dismantled between each run period. The positions of the CsI boxes were found to be stable for all runs. After the run in March 1995, the CDE detectors were replaced by the CFB detectors. The positions of the CFB

detectors changed significantly from run to run. Both the left and the right CFB detectors were generally put a few degrees off in the backward direction and a few degrees off in the upward direction as compared to the design positions. The results for all run periods are presented in table 4.1. The positions are expressed with respect to a reference point in the centre of each CFB detector plane. The design positions of the reference points are situated at 60 degrees in scattering angle and at 180 or 0 degrees in azimuthal angle for the right and left CFB detector respectively.

4.2.2 Beam energy

The beam energy is given by the circumference of the circulating beam (L) and the radio frequency of the accelerator cavities (f) as:

$$T_p = mc^2 \left(\frac{1}{\sqrt{1 - \beta^2}} - 1 \right), \beta = \frac{fL}{c} \quad (4.1)$$

The radio frequency is known to a high precision. The circumference cannot, however, be measured with the same precision. Furthermore, it is not known whether the circumference remains the same at all beam energies or if it changes with energy.

The electron cooler can be used to measure the beam energy at lower energies. The high voltage of the electron cooler determines the energy of the electron beam. If the high voltage is well calibrated, it can be used to get an independent value of the beam energy. For proton energies higher than 550 MeV, electron cooling is not possible to use and some other method to check the beam energy is necessary. One possibility is to use overdetermined $pp \rightarrow d\pi^+$ events and perform a kinematical fit with the beam energy as an unknown parameter. Both a 3-C fit and a 1-C fit, where the kinetic energies of the deuteron and the pion were not used in the fit, gave consistent results. The nominal and the fitted beam energies for all runs agreed within 0.5 MeV. The error of the mean value is less than 1 MeV.

The design value is 81.763 m for the circumference of the CELSIUS ring. Measurements of the beam energy using the electron cooler at a nominal beam energy of 500 MeV in the spring 2000 indicates that the circumference is 81.77 ± 0.03 m [41]. From experiments at the nominal beam energy of 1360 MeV in March 1995 [28] and September 1996 [27], the analysis showed that the actual beam energy was 1350 MeV which

corresponds to a circumference of 81.74 m. The results at the intermediate energies used in this thesis are, however, consistent with the design value of the circumference.

The momentum spread of the protons in the beam, $\Delta p/p$, is of the order of 1×10^{-3} [42], which corresponds to an energy spread of ~ 1 MeV (FWHM) for beam energies between 650 and 775 MeV.

4.2.3 Vertex position

The position of the scattering vertex depends on the horizontal and the vertical positions of the CELSIUS beam and the position of the target beam along the CELSIUS beam. The coplanarity of the deuteron and the pion in the reaction $pp \rightarrow d\pi^+$ is used to check the vertex position in the analysis. By varying the horizontal and the vertical positions of the beam in the event reconstruction and extracting the coplanarity for each combination, the best set of coordinates can be found. The beam is generally well centred in the x-direction, but 3 to 5 millimeters below the design value in the y-direction. This is in agreement with previous measurements of the vertex position [28, 27, 43]. The errors are estimated to be 2 mm in the y- and x-direction respectively. The results for all runs are shown in table 4.2.

Table 4.2. The horizontal and vertical positions of the beam.

Run period	Beam energy (MeV)	x-position (mm)	y-position (mm)
MAR95	725	-2	-5
MAR95	750	-1.5	-5
APR96	650	0	-5
APR96	750	0	-5
APR96	775	1	-5
SEP96	650	0	-3
APR97	650	0	-5
MAR98	680	-1	-5

For a two-body reaction, such as the $pp \rightarrow d\pi^+$ reaction, the scattering angle of one of the particles determines the scattering angle of the other.

This offers an opportunity to check the position of the target beam along the CELSIUS beam. For different settings of the z-position of the target, either the deuteron or the pion is used to calculate the scattering angle of the other particle. The calculated scattering angle is compared to the measured scattering angle, and the z-coordinate which gives the minimum deviation is selected. The results indicate that the z-position of the target changed from being a few millimeters behind the design position in March 1995 to a few millimeters in front of the design position for the following runs. In the autumn of 1995, a new general purpose scattering chamber was installed which could have influenced the position of the target beam. It is however difficult to distinguish between a misalignment of the FD and a shift in the z-position of the target.

4.3 Detector calibration

The calibration constants are used to translate the ADC output to kinetic energy and the TDC output to time. The energy calibration constants change from run to run due to different experimental conditions such as the high-voltage settings of the photo multipliers tubes. Each run starts with a special calibration cycle where the beam energy is ramped from 48 MeV to 400 MeV. The calibration cycle is used in the calibration procedure to extract the energy dependence of the FD calibration constants. Time calibration constants are extracted for all elements in the FHD and FRH from data on elastically scattered protons. The CD energy calibration constants are extracted using high energy gammas from the decay of neutral mesons.

4.3.1 Energy calibration of the forward detector

Energy calibration constants and light-collection efficiency parameters are extracted for each detector element in the FHD and the FRH. The detector response is non-linear due to a radial dependence of the light-collection efficiency, energy dependent photo-multiplier tubes and quenching. These three effects are corrected for independently in the energy reconstruction. In the calibration procedure however, an iterative procedure has to be used since the light-collection efficiency parameters and the energy calibration constants depend on each other.

In the first step of the calibration procedure, the light-collection ef-

efficiency parameters are extracted using elastically scattered protons at a high energy ($T_p \geq 1000$ MeV). Each detector element is divided into a number of radial bins and one of them is chosen as a reference bin. The light collection efficiency of the reference bin is set to one. High energy protons penetrate the whole detector and the energy depositions are the same at all radii, except for a small correction due to the scattering angle and the path length of the particle in the detector element. By comparing the energy depositions from the different radial bins with the energy depositions from the reference bin, light-collection efficiency parameters can be extracted. The energy depositions are calculated using preliminary energy calibration constants.

In the second step of the calibration procedure, the energy dependence of the energy calibration constants due to the non-linear response of the photo-multiplier tubes is extracted using elastically scattered protons from the energy ramping of the calibration cycle. Measured energy depositions corrected for light-collection efficiency divided by energy depositions obtained from Monte Carlo are plotted versus the measured energy depositions. The new energy calibration constants are obtained from a linear fit to the points. The measured energy depositions are calculated using calibration constants from a previous beam time or the preceding iteration. Using the new calibration constants, new light-collection efficiency parameters can be extracted. The calibration procedure is completed when the energy calibration constants and the light-collection efficiency parameters do not change significantly from one iteration to the next.

In March 1995 a full calibration of the FD was performed as described above [44]. A simplified calibration procedure was used to calibrate the following runs since the light-collection efficiency parameters did not change significantly from run to run. In order to extract the energy dependence of the energy calibration constants in the simplified calibration procedure, different energy depositions were obtained using energy depositions from several radial bins corrected for light-collection efficiency instead of energy depositions collected at different beam energies from the energy ramping of the calibration cycle. Since the light-collection efficiency parameters are assumed to be correct, only the second step of the calibration procedure is repeated until the energy calibration constants do not change significantly from one iteration to the next.

4.3.2 Time calibration of the forward detector

All elements in the PROMICE/WASA detector are connected to TDCs. When a particle hits an element, the corresponding TDC is started. The time of the hit is defined as the time interval between the start of the TDC and the common stop from the trigger system. The time information is used in the track reconstruction to put generous constraints on which hit clusters belong to a certain track. The time information is also used to identify positive pions with the delayed pulse technique described in section 4.6.2.

Tracks from elastically scattered protons with hits in all layers of the FD are selected in the calibration procedure. Since it is only the relative time between different elements that can be extracted, all elements in the FHD and the FRH are calibrated with respect to a reference element in the first layer of the FRH.

4.3.3 Energy calibration of the central detector

Gammas from the decay of π^0 :s and η :s are used to extract the energy calibration constants. The invariant mass of the two gammas is calculated and the invariant mass distributions from real data are fitted to invariant mass distributions obtained from Monte Carlo data.

A high energy gamma produces a shower in a CsI box. The centre of gravity of the shower usually lies within one crystal and the energy deposition in that crystal is about 70 percent of the total shower energy. Events with a gamma shower which has its centre of gravity in only one crystal and a detected gamma in the opposite CsI box are selected in the calibration procedure. The invariant mass (m) is calculated according to equation 4.2 where θ is the opening angle of the gammas, E_1 is the deposited energy in the crystal and E_2 is the deposited energy in the opposite CsI box.

$$m = 2 \cdot \sin\left(\frac{\theta}{2}\right) \cdot \sqrt{E_1 E_2} \quad (4.2)$$

The new calibration constants are obtained by fitting the invariant mass distributions from real data to invariant mass distributions from Monte Carlo data for each element. If all the energy is deposited in one crystal and the total energy from the opposite CsI box is correctly measured,

it would be possible to get the correct calibration constants from one iteration. In reality, a few iterations are necessary.

The reconstructed invariant masses are products of the energies measured in the right and in the left CsI boxes. The calibration constants of one CsI box could be systematically higher as compared to the calibration constants of the other, without changing the value of the reconstructed invariant mass. The average energy depositions in the right and left CsI boxes are therefore required to be equal in the calibration procedure.

The energy depositions of gammas is different from the energy depositions of charged particles. The calibration constants obtained with the method described above cannot be used for charged particles. To avoid problems with energy leakage out of the detector, only the inner crystals are used in the analysis and hence only the inner crystals are calibrated.

4.4 Energy reconstruction

The kinetic energy is reconstructed in the analysis using the calibration constants obtained in the calibration procedure and, in the case of charged particles, compensating the deposited energy for quenching and energy loss in dead material. The light pulser system, described in section 3.5, is used to compensate the energy calibration constants for any change in the gain of the detector elements during the run. Two types of variations in the gain were observed, short- and long-time variations. The short-time variations were connected to the accelerator cycle and were usually on a 5 percent level. Some elements also showed long-time variations over several hours on a 15 percent level. The origin of these variations are not known. The light pulser system is however able to correct the reconstructed energy for these variations in almost all cases.

4.4.1 The forward detector

The ADC content of each element is first translated to deposited energy using the energy calibration constants obtained in the second step of the calibration procedure. After the signals from the detector elements that were hit have been combined into tracks, the radial impact position is calculated and the deposited energy is corrected for the light-collection efficiency using the light-collection efficiency parameters obtained in the first step of the calibration procedure. Finally, when the tracks have been

identified with particles, the kinetic energy is calculated by correcting the deposited energy for quenching, described below, and energy loss in dead material.

Quenching is a saturation effect in the scintillator material. High ionization densities give less light output as compared to the same amount of energy being deposited with lower ionization densities. The ionization density depends on the charge and velocity of the ionizing particle which means that at a given momentum, quenching increases with charge and mass of the ionizing particle. The quenching correction for protons is usually one order of magnitude larger than the quenching correction for charged pions.

4.4.2 The central detector

The deposited energy for gammas is calculated using the first order calibration constants obtained in the calibration. To get the correct kinetic energy, the deposited energy has to be corrected for energy leakage into other crystals. The correction factor is obtained from Monte Carlo and is usually between 6 and 7.5 percent. The kinetic energy for elastically scattered protons detected in the CD is not needed in the analysis.

4.5 Track reconstruction

The track reconstruction routine is designed to work even in case of bad geometrical alignment, bad timing or bad detection efficiency. It is therefore very general and combines the available hits to a number of possible track candidates. The advantage of this approach is that it allows the user to decide which tracks to keep in the analysis depending on how well the detector is understood and the specific reaction in question. Additional constraints are put on the tracks after all possible track candidates have been formed and the most likely ones are selected for further analysis.

The track reconstruction is performed in three steps. First, the hits in each separate detector plane are combined into hit clusters. For each hit cluster, the mean element number, the mean time and the mean energy deposition are calculated. Second, the hit clusters in the separate detector planes are combined into detector tracks. The maximum element deviation allowed for two clusters in different planes is one, counted from the first element in the track. Third, the tracks in the separate detectors

are combined into forward/central detector tracks. A forward/central detector track can contain one or more detector tracks.

4.5.1 The forward detector

The most difficult reaction to handle in the track reconstruction is the $pp \rightarrow pp\pi^+\pi^-$ reaction. If all outgoing particles end up in the FD, four tracks have to be reconstructed. It is however difficult to reconstruct more than three tracks unambiguously in the FD and subsequently, only events with three charged tracks in the FD are kept in the analysis. The other two reactions, $pp \rightarrow pp\pi^0\pi^0$ and $pp \rightarrow pn\pi^+\pi^0$, can at most give two charged tracks in the FD, which is straightforward to reconstruct.

The number of track candidates formed in the initial track reconstruction for events picked out by the main trigger to select three charged tracks in the FD are shown in Fig. 4.2(a). Several conditions are put on each charged FD track candidate in order to select the most likely tracks from the track candidates.

- A track is required to have a hit in all planes until it stops. Otherwise part of deposited energy belonging to the track is lost.
- A track must have a hit in at least the first plane of the FRH. The energy reconstruction using only the FHD is not reliable.
- A track is not allowed to have a hit in the FVH. Only a part of the deposited energy belonging to the track can be measured if it passes through the FRH.
- The scattering angle of a track must be between 4 and 23 degrees. If the scattering angle is less than 4 degrees, part of the track could be inside the beam pipe. If the scattering angle is greater than 23 degrees, the track may escape the FRH, thereby making the energy determination unreliable.
- Tracks that share a hit cluster are discarded. It is not possible to determine to which track the energy deposition belong, when two tracks share a hit cluster.

The result of the additional conditions put on each track candidate is shown in Fig. 4.2(b). Most of the tracks formed in the initial track reconstruction are non-physical.

(a) The number of track candidates formed in the initial track reconstruction.

(b) The number of tracks after the additional conditions have been put on the track candidates formed in the initial track reconstruction.

Figure 4.2. The number of track candidates in the FD at different stages of the track reconstruction for events picked out by the main trigger to select three charged tracks in the FD.

4.5.2 The central detector

The only neutral particles detected in the CD for the reactions studied in this thesis are gammas from the decay of neutral pions. A track is considered as a neutral track if it has a hit in a CsI box and no hits in the CD $\Delta E_1/\Delta E_2$ detector in front of the box. Up to four gammas can end up in the CD for the $pp \rightarrow pp\pi^0\pi^0$ reaction. It is however difficult to reconstruct more than one neutral track in each CsI box, and therefore only events with one detected gamma in each box are kept in the analysis. Protons from elastic scattering are the only charged particles that are detected in the CD. A track is considered as a charged CD track if it has a hit in the central $\Delta E_1/\Delta E_2$ detector and a hit in the corresponding CsI box.

4.6 Particle identification

The charged outgoing particles from the two-pion production reactions are detected in the FD. The particles are first identified from their energy

loss in the different layers of the FHD and FRH using the $\Delta E_1/\Delta E_2$ method. While this method is sufficient to identify protons, charged pions need an additional identification method. Positive pions can be identified with the delayed pulse technique [45], discussed below. Negative pions cannot be identified in the FD as they are absorbed by nuclei in the detector before they decay. Neutral particles are not identified in the FD with the exception of neutrons from the $pp \rightarrow pn\pi^+\pi^0$ reaction.

Gammas from the decay of the neutral pions are identified in the CD from the condition that the tracks have no hits in the CD $\Delta E_1/\Delta E_2$ detector. The neutral pions are then identified from the invariant mass of the two gammas.

4.6.1 The $\Delta E_1/\Delta E_2$ method

Heavy particles, i.e. particles heavier than the electron, that pass the detector lose their kinetic energy almost solely from inelastic collisions with the atomic electrons of the material, causing the atoms to be ionized or excited [46]. The inelastic collisions occur with a certain quantum mechanical probability and are statistical in nature. The fluctuations in energy loss for a certain particle are however small due to the large number of collisions per unit length.

The energy loss per unit length reaches a minimum which is almost constant for all particles with the same charge at $v \simeq 0.96c$. At lower velocities, the energy loss behaviour is usually different for different particles. This feature is used in the $\Delta E_1/\Delta E_2$ method to identify charged particles in the detector.

The $pp \rightarrow pp\pi^+\pi^-$ reaction

The selection of protons and pions from the $pp \rightarrow pp\pi^+\pi^-$ reaction at 650 MeV is illustrated in Fig. 4.3. The same limits are used for all run periods at this energy. The limits are generous to avoid losing particles with bad energy information.

The main background at 650 MeV comes from the $pp \rightarrow pp\pi^0$ reaction. The gammas from the decay of the π^0 can convert to electron-positron pairs in the material surrounding the interaction region. If an electron or a positron ends up in the FD together with the two outgoing protons, the trigger used to pick out charged two-pion production is activated. The selection is further complicated by the fact that the energy loss behaviour

(a) Experimental data at 650 MeV

(b) Monte Carlo generated data at 650 MeV

(c) Experimental data at 680 MeV

(d) Monte Carlo generated data at 680 MeV

Figure 4.3. $\Delta E_1/\Delta E_2$ selection of protons and pions from the $pp \rightarrow pp\pi^+\pi^-$ reaction.

of electrons and positrons is similar to that of charged pions. The background from electrons and positrons can be seen in Fig. 4.3(a) as an island of entries in the lower left corner. The two other important background reactions, $pp \rightarrow pn\pi^+/d\pi^+$, give smaller contributions at this energy. A small enhancement of entries can however be seen in Fig. 4.3(a) originat-

ing from deuterons. Comparing Fig. 4.3(a) and Fig. 4.3(b), which shows Monte Carlo generated events, it is obvious that it is difficult to identify charged pions using only the $\Delta E_1/\Delta E_2$ method.

At 680 MeV, the background reaction $pp \rightarrow pn\pi^+$ gives a significant contribution. The neutron in the $pp \rightarrow pn\pi^+$ reaction can undergo a n-p reaction in the forward cone of the scattering chamber or in the FWC. If the proton ends up in the FD together with the outgoing proton and the positive pion, the trigger used to pick out events with three charged tracks in the FD is activated. In addition to the background present at 650 MeV, positive pions from the $pp \rightarrow pn\pi^+$ reaction form another island of events to the right of the island formed by electrons and positrons as is shown in Fig. 4.3(c). To avoid saving a lot of background events in the analysis, less generous limits at 680 MeV as compared to at 650 MeV are used. From the Monte Carlo generated data shown in Fig. 4.3(d), it can be seen that the limits are still quite generous.

The $pp \rightarrow pp\pi^0\pi^0$ and $pp \rightarrow pn\pi^+\pi^0$ reactions

The selection of protons and pions from the $pp \rightarrow pp\pi^0\pi^0$ and $pp \rightarrow pn\pi^+\pi^0$ reactions is illustrated in Fig. 4.4(a) with data from March 1995 at 725 MeV. The same limits are used for all energies and run periods except for data from the run in April 1996, when more generous limits are used since the calibration of the FD is not as good as for the other runs. Monte Carlo generated data for the $pp \rightarrow pp\pi^0\pi^0$ and $pp \rightarrow pn\pi^+\pi^0$ reactions are shown in Fig. 4.4(b). Again, comparing Fig. 4.4(a) and Fig. 4.4(b), it is apparent that the positive pions need further identification.

The trigger to pick out the two-pion production events with one or two neutral pions in the final state was very selective and the only background reaction which gives a significant contribution is the $pp \rightarrow pp\pi^0$ reaction. This is despite the fact that the detection acceptance for the $pp \rightarrow pp\pi^0$ reaction is very small at the energies studied in this thesis. The total cross section for the $pp \rightarrow pp\pi^0$ reaction is however $\sim 10^3$ larger than the total cross sections for the two-pion production reactions at the energies studied in this thesis.

The neutral pions are identified from the invariant mass of the two gammas. This is straightforward in the case of the $pp \rightarrow pn\pi^+\pi^0$ reaction where only two gammas can end up in the CD. For the $pp \rightarrow pp\pi^0\pi^0$ reaction, the situation is more involved. Only events with one gamma

Figure 4.4. $\Delta E_1/\Delta E_2$ selection of protons and pions from the $pp \rightarrow pp\pi^0\pi^0$ and $pp \rightarrow pn\pi^+\pi^0$ reactions. Both reactions are included in the Monte Carlo generated data.

in each CsI box are kept in the analysis but up to four gammas can end up in the CD. In principle, it is possible to find out if the detected gammas come from the same π^0 or not. In reality, this turns out to be difficult due to the limited angular and energy resolution of the CD. One way to determine if the two detected gammas from the $pp \rightarrow pp\pi^0\pi^0$ reaction come from the same π^0 or not, is to use kinematical fitting. The advantages and disadvantages with this method are further discussed in section 4.7.2.

Neutrons from the $pp \rightarrow pn\pi^+\pi^0$ reaction are partly reconstructed in the analysis. A FD track is considered to be neutral if it has no hits in the tracker or the FHD and at least one hit in the FRH. It is not possible to reconstruct the deposited energy for neutral tracks, nor can the scattering angle be reconstructed since no information from the tracker or the FHD is available. It is however possible to reconstruct the azimuthal angle from the hit information in the FRH. The probability to detect the neutron in any layer of the FRH from the $pp \rightarrow pn\pi^+\pi^0$ reaction at the energies studied in this thesis is between 35-40 percent [47]. Subsequently, in 35-40 percent of the cases, when an event is identified as coming from the $pp \rightarrow pn\pi^+\pi^0$ reaction, a neutron with the correct azimuthal angle should be found. This is further discussed in section 4.7.3.

4.6.2 The delayed pulse technique

The identification of pions from the energy loss information alone is not sufficient. In the absence of a magnetic field, the pions can be identified by detecting the particles coming from their decay. This technique only works for positive pions, however, since negative pions are captured in atomic orbits and subsequently absorbed by nuclei in the detector before they decay. In matter, e.g. in a scintillator, the positive pions stop and decay according to Eq. 4.3 and Eq. 4.4, where τ is the mean life time of the decay.

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \quad \tau = 26 \text{ ns} \quad (4.3)$$

$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu \quad \tau = 2197 \text{ ns} \quad (4.4)$$

Either the signal from the μ^+ or the e^+ can be used to identify the positive pions. Detecting the fast signal from the μ^+ allows for high event rates but requires a very good time resolution of the FD. For this reason, the slower signal from the e^+ is used in the delayed pulse technique. The drawback using the slower signal is that the time windows of the multi-hit TDCs have to be large, in this case [160 ns - 6 μ s]. Particles entering the detector when the time window is open can be mistaken for delayed signals from the pion decay. To take care of accidental delayed signals, one plane connected to the multi-hit TDCs is used as a veto plane.

There are several options implemented in the delayed pulse technique to search for delayed signals in the FD. The highest efficiency is obtained when a delayed signal is searched for in the element where the particle stopped as well as in all adjacent elements and the third layer of the FHD is used as a veto plane. The delayed-pulse times for all particles identified as pions in the $\Delta E_1/\Delta E_2$ method from the reaction $pp \rightarrow pp\pi^+\pi^-$ at 650 MeV are shown in Fig. 4.5(a). The peak at ~ 430 ns corresponds to signals that are reflected in the cables connecting the detector elements with the TDCs. The delayed-pulse times for all particles discarded by the veto for the same set of data are shown in Fig. 4.5(b). The periodic variation corresponds to the time it takes for a bunch of beam particles to complete one turn in the CELSIUS ring.

The kinetic energy of the muon is 4.2 MeV in the rest system of the pion. This energy can contribute to the energy deposited by the pion in the FD if the decay occurs within the 200 ns time window of the ADC,

(a) The delayed-pulse times for all particles identified as positive pions for events from the $pp \rightarrow pp\pi^+\pi^-$ reaction at 650 MeV.

(b) The delayed-pulse times for all particles discarded by the veto for events from the $pp \rightarrow pp\pi^+\pi^-$ reaction at 650 MeV.

(c) All pions identified using only the $\Delta E_1/\Delta E_2$ method for events from the $pp \rightarrow pp\pi^+\pi^-$ reaction at 680 MeV. (cf. Fig. 4.3(c))

(d) All pions identified with the delayed pulse technique in addition to the $\Delta E_1/\Delta E_2$ information for events from the $pp \rightarrow pp\pi^+\pi^-$ reaction at 680 MeV.

Figure 4.5. The selection of positive pions using the delayed pulse technique.

thereby distorting the energy information from the pion. The maximum kinetic energy of the e^+ is 52.3 MeV. Considering the slow decay time of the μ^+ , it is not likely that this energy contributes to the measured energy of the positive pion. Fig. 4.5(c) shows all particles identified as pions in the $\Delta E_1/\Delta E_2$ method for the reaction $pp \rightarrow pp\pi^+\pi^-$ at 680 MeV and Fig. 4.5(d) shows the positive pions identified by the delayed pulse technique for the same set of data.

4.7 Event selection

The events that pass the track reconstruction, the energy reconstruction and the particle identification must fulfil certain requirements on the number of identified particles to be kept in the last two steps of the analysis, the event identification and the physics analysis. The selected events are stored on an event-by-event basis in Ntuples. The use of Ntuples makes it easy to study how different kinematical variables depend on each other and how different cuts influence the two-pion production events and the background events respectively. Monte Carlo is an important tool in understanding the experimental data. Monte Carlo generated data of the two-pion production reactions as well as the background reactions are processed in parallel with experimental data throughout the event identification and physics analysis.

4.7.1 The $pp \rightarrow pp\pi^+\pi^-$ reaction

The $pp \rightarrow pp\pi^+\pi^-$ event candidates with two protons and one pion, where the pion is identified using only the $\Delta E_1/\Delta E_2$ method, are selected and stored in Ntuples for further analysis. Since no delayed pulse from the pion is demanded, the selected subsets of the original data contain events with either a positive or a negative pion as well as a substantial amount of background events from one-pion production reactions.

The missing mass distribution of the two protons and the pion for all selected events at 650 MeV is shown in Fig. 4.6(a). The presence of the $pp \rightarrow pp\pi^+\pi^-$ reaction can be seen as a small increase of events around the mass of a charged pion. The events which remain when the pion is required to have a delayed pulse are shown by the solid line in Fig. 4.6(b). The peak around the mass of a charged pion is now apparent. The delayed pulse technique effectively removes the events from the

dominating background reaction, $pp \rightarrow pp\pi^0$. The background events still present in Fig. 4.6(b) are mainly due to the $pp \rightarrow pn\pi^+$ reaction, where the positive pion is correctly identified by the delayed pulse technique. The background can be further reduced by making cuts on the proton-proton opening angle, the scattering angles of the protons, the kinetic energies of the protons and the kinetic energy of the positive pion. The events that remain after the physical cuts have been applied are shown by the shaded histogram in Fig. 4.6(b).

The missing mass distribution of the two protons and the pion for the selected event candidates at 680 MeV is shown in Fig. 4.6(c). As mentioned earlier, the limits used in the $\Delta E_1/\Delta E_2$ selection of protons and pions at 680 MeV are less generous as compared to the limits used at 650 MeV. The background from one-pion production reactions is therefore suppressed in the selected event sample at 680 MeV. In particular, the background from the $pp \rightarrow pn\pi^+$ reaction is effectively removed by the cut on a maximum deposited energy for the pion. The solid line in Fig. 4.6(d) shows the events which remain when the pion is required to have a delayed pulse. The background can be further reduced by making a refined $\Delta E_1/\Delta E_2$ selection of protons and pions using different layers of the FRH and by making physical cuts of the same kind as those used at 650 MeV. The events that remain after all cuts have been applied are shown by the shaded histogram in Fig. 4.6(d).

The number of events used to calculate the total cross section at each energy for the $pp \rightarrow pp\pi^+\pi^-$ reaction is extracted by selecting a region around the mass of a charged pion in the missing mass distribution of the two protons and the positive pion before any physical cuts have been made. The background is removed by a smooth fit to the background on both sides of the peak. The events which are used in the final kinematical distributions are selected by making a cut on the missing mass of the two protons and the pion as well as a cut on the missing mass of the two protons after the physical cuts have been applied. The kinematical distributions will contain a small amount of background events which cannot be discarded by the physical cuts.

4.7.2 The $pp \rightarrow pp\pi^0\pi^0$ reaction

The selection of $pp \rightarrow pp\pi^0\pi^0$ event candidates is straightforward. All events with two protons in the FD and one gamma in each CD box are

(a) All selected events at 650 MeV where the two protons and the pion are identified with the $\Delta E_1/\Delta E_2$ method and no delayed pulse from the positive pion is required.

(b) All selected events at 650 MeV with the requirement of a delayed pulse from the positive pion (solid line) and the events which remain after cuts on opening angles, scattering angles and kinetic energies (shaded histogram).

(c) All selected events at 680 MeV where the two protons and the pion are identified with the $\Delta E_1/\Delta E_2$ method and no delayed pulse from the positive pion is required.

(d) All selected events at 680 MeV with the requirement of a delayed pulse from the positive pion (solid line) and the events which remain after a refined $\Delta E_1/\Delta E_2$ selection, cuts on opening angles, scattering angles and kinetic energies (shaded histogram).

Figure 4.6. The missing mass distributions of two protons and one pion for $pp \rightarrow pp\pi^+\pi^-$ event candidates at 650 and 680 MeV at different stages of the event selection.

stored in Ntuples for further analysis. The selected event samples do not contain much background. The only background reaction which gives a significant contribution is neutral one-pion production.

The missing mass distribution of the two protons for all selected events at 650 Mev is shown by the solid line in Fig. 4.7(a). The $pp \rightarrow pp\pi^0\pi^0$ events should show up as an enhancement of events around the summed mass of two neutral pions. The background events from neutral one-pion production gives a relatively large contribution at this energy. The event sample can be cleaned up by making a refined $\Delta E_1/\Delta E_2$ selection of protons using different layers of the FRH and by making cuts on the proton-proton opening angle, the scattering angles of the protons and the kinetic energies of the protons. The events that remain after the physical cuts have been applied are shown by the shaded histogram in Fig. 4.7(a).

The missing mass distributions of the two protons for all selected events at 725, 750 and 775 Mev are shown in Figs. 4.7(b)(c)(d). No physical cuts are meaningful at these energies due to the limited detection acceptance for protons from the $pp \rightarrow pp\pi^0\pi^0$ reaction. Fortunately, the total cross section for neutral two-pion production rises sharply with increased beam energy whereas the total cross section for neutral one-pion production only increases by a factor of two in the energy region between 650 to 775 MeV.

The number of events used to calculate the total cross section at each energy is extracted by selecting all events in a region around the summed mass of two neutral pions in the missing mass distribution of the two protons. The background from neutral one-pion production must be subtracted and the shape of the background in the selected region is taken from Monte Carlo simulations of the background reactions.

The events which are used in the kinematical distribution can be selected in two ways. The first option is to select all events in a region around the summed mass of two neutral pions in the missing mass distribution of the two protons. This will however give event samples which contain some background from neutral one-pion production. Another option is to use kinematical fitting. This will give clean event samples but at the expense of a limited selection efficiency, i.e. some of the good events will be lost. Several fits are necessary to select the $pp \rightarrow pp\pi^0\pi^0$ events. First, a 1-C fit is performed to determine if the two detected gammas come from the same π^0 or not. If not, the event should come from the $pp \rightarrow pp\pi^0\pi^0$ reaction, since no other reaction at these energies

(a) All selected events at 650 MeV (solid line) and the events which remain with cuts on the proton-proton opening angle, proton scattering angles and proton kinetic energies in addition (shaded histogram).

(b) All selected events at 725 MeV. No physical cuts can be applied at this energy due to the limited detection acceptance for protons from the $pp \rightarrow pp\pi^0\pi^0$ reaction.

(c) All selected events at 750 MeV from March 1995. No physical cuts can be applied at this energy due to the limited detection acceptance for protons from the $pp \rightarrow pp\pi^0\pi^0$ reaction.

(d) All selected events at 775 MeV. No physical cuts can be applied at this energy due to the limited detection acceptance for protons from the $pp \rightarrow pp\pi^0\pi^0$ reaction.

Figure 4.7. The missing mass distributions of two protons for $pp \rightarrow pp\pi^0\pi^0$ event candidates at 650, 725, 750 and 775 MeV at different stages of the event selection.

(a) All events with two protons in the FD and one gamma in each CD box.

(b) All events with two protons in the FD and one gamma in each CD box selected by the kinematical fit procedure.

Figure 4.8. The missing mass distributions of two protons for $pp \rightarrow pp\pi^0\pi^0$ events candidates at 750 MeV before and after the kinematical fit procedure.

can give more than one neutral pion in the final state. If the two gammas come from the same π^0 , the event is reconstructed under the two assumptions that it comes from either neutral one- or two-pion production. A 2-C fit is performed for the $pp \rightarrow pp\pi^0\pi^0$ hypothesis and a 5-C fit is performed for the $pp \rightarrow pp\pi^0$ hypothesis. The event is then sorted into one of the three possible event categories, neutral one-pion production, neutral two-pion production or none of the two depending on the probabilities of the different kinematical fits. The effect of the kinematical fit procedure is illustrated in Fig. 4.8. All selected events at 750 MeV with two protons in the FD and one gamma in each CD box are shown in Fig. 4.8(a) and the events that remain after the kinematical fit procedure are shown in Fig. 4.8(b). The kinematical fit removes almost all of the background under the peak corresponding to neutral two-pion production. Kinematical fitting can also be used to improve the resolution of kinematical variables such as missing mass and invariant mass distributions. The kinematical fit procedure is however not used to extract the number of events to calculate the total cross section since the selection efficiency cannot be determined with sufficient accuracy.

4.7.3 The $pp \rightarrow pn\pi^+\pi^0$ reaction

All $pp \rightarrow pn\pi^+\pi^0$ event candidates with one proton in the FD, one gamma in each CD box and one pion identified with the $\Delta E_1/\Delta E_2$ method in the FD are selected and stored in Ntuples for further analysis. The selected event samples contain a significant amount of background events from reactions with one or two neutral pions in the final state.

The missing mass distributions of the proton and the two pions for all selected events at 725 and 775 MeV are shown by the solid lines in Fig. 4.9. The corresponding distribution for all selected events at 750 MeV is shown by the solid line in Fig. 4.10(a). The events from the $pp \rightarrow pn\pi^+\pi^0$ reaction should show up as an increase of events around the mass of a neutron in the missing mass distributions of the proton and the two pions. Although the peaks around the neutron mass are apparent, most of the events come from the $pp \rightarrow pp\pi^0$ and $pp \rightarrow pp\pi^0\pi^0$ reactions, where one of the protons is misidentified as a charged pion in the $\Delta E_1/\Delta E_2$ selection. The leftmost peaks in the missing mass distributions correspond to events from the $pp \rightarrow pp\pi^0$ reaction and the rightmost peaks correspond to events from the $pp \rightarrow pp\pi^0\pi^0$ reaction together with the wanted events from the $pp \rightarrow pn\pi^+\pi^0$ reaction.

The background from neutral one- and two-pion production can be removed with the delayed pulse technique. The shaded histograms in Fig. 4.9 and Fig. 4.10(a) show the effect of the additional condition that the positive pions must have a delayed pulse. The delayed-pulse times for all particles identified as positive pions with the delayed pulse technique are shown in Fig. 4.10(b). A fit to the slope gives a value of 2192 ns for the mean life time of positive muons, in excellent agreement with the text book value of 2197 ns [48]. It is therefore reasonable to assume that almost all events picked out by the delayed pulse technique have a positive pion in the final state.

If the positive pions are correctly identified and the two gammas come from either the same or two different neutral pions, only two reactions are possible, the $pp \rightarrow pn\pi^+\pi^0$ and the $pp \rightarrow d\pi^+\pi^0$ reactions. The $pp \rightarrow d\pi^+\pi^0$ events are however difficult to separate from the $pp \rightarrow pn\pi^+\pi^0$ events. The $pp \rightarrow d\pi^+\pi^0$ events pass the event selection in two ways. Either the deuteron is misidentified as a proton in the $\Delta E_1/\Delta E_2$ selection or the deuteron breaks up into a neutron and a proton in the detector material and the proton is subsequently identified in the $\Delta E_1/\Delta E_2$ selection.

(a) All selected events at 725 MeV (solid line) and the events which remain when a delayed pulse from the pion is required in addition (shaded histogram).

(b) All selected events at 775 MeV (solid line) and the events which remain when a delayed pulse from the pion is required in addition (shaded histogram).

Figure 4.9. The missing mass distributions of a proton and two pions for $pp \rightarrow pn\pi^+\pi^0$ event candidates at 725 and 775 MeV at different stages of the event selection.

Most of the background from the $pp \rightarrow d\pi^+\pi^0$ events can be discarded by making a cut on the minimum scattering angle of the particle identified as a proton. The deuterons and the protons from deuteron breakup originating from the $pp \rightarrow d\pi^+\pi^0$ reaction have small scattering angles. In fact, many of them disappear in the beam pipe, thereby escaping detection. The scattering angles of the protons from the $pp \rightarrow pn\pi^+\pi^0$ reaction on the other hand, are distributed over the available detector acceptance. The distribution in scattering angle of the particle identified as a proton for $pp \rightarrow pn\pi^+\pi^0$ event candidates at 750 MeV, selected with a requirement of a delayed pulse from the pion and a cut on the missing mass of the proton and the two pions, is shown by the points in Fig. 4.10(c). The dashed and dotted lines show the result of a full Monte Carlo simulation for the $pp \rightarrow pn\pi^+\pi^0$ reaction and $pp \rightarrow d\pi^+\pi^0$ reactions respectively. The solid line shows the sum of the two Monte Carlo distributions. The agreement between the experimental distribution and the summed Monte Carlo distribution is reasonable.

As mentioned in section 4.6.1, the probability to detect the the neu-

(a) The missing mass distribution of the proton and the two pions for all selected events at 750 MeV (solid line) and for all events with a delayed pulse from the pion (shaded histogram).

(b) The delayed-pulse times for all particles identified as positive pions with the delayed pulse technique. A fit to the slope gives a value of 2192 ns for the mean life time of positive muons.

(c) The scattering angle of the proton detected in the FD. The points show real data. The dashed and dotted lines show Monte Carlo generated data from the $pp \rightarrow pn\pi^+\pi^0$ and the $pp \rightarrow d\pi^+\pi^0$ reactions respectively. The solid line shows the sum of the two contributions.

(d) The difference between the measured and reconstructed azimuthal angle for the neutron. The points show real data. The dashed and dotted lines show Monte Carlo generated data from the $pp \rightarrow pn\pi^+\pi^0$ and the $pp \rightarrow d\pi^+\pi^0$ reactions respectively. The solid line shows the sum of the two contributions.

Figure 4.10. The selected $pp \rightarrow pn\pi^+\pi^0$ event candidates at 750 MeV at different stages of the event selection and the event identification.

tron from the $pp \rightarrow pn\pi^+\pi^0$ reaction in any layer of the FRH is between 35 and 40 percent. This can be used as a consistency check on the number of identified $pp \rightarrow pn\pi^+\pi^0$ events. The same technique has been used in a previous PROMICE/WASA experiment to check the consistency of the number of identified $pn \rightarrow pn\eta$ events in proton-neutron collisions using a deuterium target [28]. The azimuthal angle of the neutron can be reconstructed since all remaining outgoing particles from the $pp \rightarrow pn\pi^+\pi^0$ reaction are measured in the experiment. The difference between the measured and the reconstructed azimuthal angle of the neutron for $pp \rightarrow pn\pi^+\pi^0$ event candidates at 750 MeV is shown by the points in Fig. 4.10(d). The number of detected neutrons with an acceptable difference between reconstructed and measured azimuthal angle of the neutron varies between 30 and 35 percent of the total number of $pp \rightarrow pn\pi^+\pi^0$ events at the different energies studied in this thesis. This is in reasonable agreement with what is expected. The dashed and dotted lines show the result of a full Monte Carlo simulation for the $pp \rightarrow pn\pi^+\pi^0$ reaction and the $pp \rightarrow d\pi^+\pi^0$ reaction respectively. If the two contributions are added, as shown by the solid line in Fig. 4.10(d), the experimental distribution is quite well described.

The number of $pp \rightarrow pn\pi^+\pi^0$ events used to calculate the total cross section at each energy is extracted by selecting a region around the mass of a neutron in the missing mass distribution of the proton and the two pions. As is obvious from looking at Figs. 4.10(c)(d) this is not enough to discard the background events from the $pp \rightarrow d\pi^+\pi^0$ reaction. The contribution from the $pp \rightarrow d\pi^+\pi^0$ reaction is therefore estimated from Monte Carlo simulations. In particular, the distribution in scattering angle of the particles identified as the proton is important. At the lowest energy, 650 MeV, the low cross section in combination with the low detection acceptance made it difficult to extract a total cross section.

4.8 Normalization

The two-pion production reactions studied in this thesis are normalized using elastically scattered protons recorded in parallel. The integrated luminosity is extracted comparing the number of detected elastically scattered protons with known cross sections. The advantage of this method to normalize the data is that the dead time of the data acquisition system, the beam intensity and the target thickness do not have to be known.

4.8.1 Selection of elastic scattering events

The two triggers used to pick out the normalization events are described in section 3.6. The normalization triggers are prescaled in the experiments due to their high rates. During the April 1997 run however, the prescaling TDC for the trigger used to select the elastic scattering events did not work. Instead, the events were selected from the normal trigger TDC spectrum, shown in Fig. 4.11. The normalization trigger connected to a normal TDC is set for nearly all events with at least one charged track in the FD. The events corresponding to when the trigger started the DAS show up as a sharp peak around 2750 ns in Fig. 4.11. Selecting the events in a narrow region around this peak gives only a small additional background as compared to if the events could have been selected from the prescaled TDC spectrum.

The trigger to select elastically scattered protons pick out events with one charged track in the FD. In the analysis, the events are required to have a corresponding charged track in the CD. At the beam energies studied in this thesis, the protons detected in the FD pass through the detector whereas those detected in the CD stop. Both the FD and the CD tracks are required to have hits in all layers of the FD and CD respectively. Only the scattering angles of the detected protons are needed to identify the elastic scattering events. The kinetic energies of the protons are therefore not reconstructed in the energy reconstruction nor are the protons identified as protons in the particle identification.

The CD covers scattering angles between 30 and 90 degrees. The windows of the scattering chamber stop protons with kinetic energies below 11 MeV. The kinetic energy of elastically scattered protons at 90 degrees is zero. To avoid inefficiency problems with protons stopping in the windows of the scattering chamber or in the central $\Delta E_1/\Delta E_2$ detectors, the protons detected in the FD are required to have scattering angles between 16 and 21 degrees. With this condition, the maximum scattering angle of the protons detected in the CD is below 70 degrees. Protons scattered elastically at this and lower angles have kinetic energies above 60 MeV at all beam energies studied in this thesis. As a result of the narrow selection in scattering angle, only a few of the vertical elements in the central $\Delta E_1/\Delta E_2$ detectors are used in the analysis.

The central $\Delta E_1/\Delta E_2$ detector used in March 1995 consisted of one plane providing information on the scattering angle for charged particles.

Figure 4.11. The normal trigger TDC spectrum for the trigger used to pick out the elastic scattering events from the run in April 1997 at 650 MeV. The events corresponding to when the trigger started the DAS show up as a sharp peak around 2750 ns.

Figure 4.12. Elastically scattered protons detected in the CD from the run in September 1996 at 650 MeV. The broken element just below the middle of the horizontal plane is apparent as are the two not connected elements in the horizontal plane at lower azimuthal angles.

One element in the CDE detector covered one column of elements in the CsI boxes. The new central $\Delta E_1/\Delta E_2$ detector used during the runs in April 1996 and onwards, consisted of two planes providing information on both scattering and azimuthal angle for charged particles. One element in the CFB detector covered roughly a third of a row or a column of elements in the CsI box, thus improving the angular resolution in both angles. Due to the flat distribution in azimuthal angle for elastic scattering events, all of the elements in the new horizontal planes are used in the analysis. However, for all runs with the CFB detector, except during the run in March 1998, two elements in the horizontal planes on both sides were not connected. In addition, between one and three elements in the horizontal planes were broken during all runs. The azimuthal angle versus the scattering angle for elastically scattered protons detected in the right CFB detector for data collected in September 1996 is shown in Fig. 4.12. A broken element in the middle of the right horizontal CFB plane is apparent as are the two not connected elements at lower azimuthal angles.

Once the scattering angles of the two protons have been reconstructed, it is straightforward to identify the elastic scattering events using Eq. 4.5,

where θ_{FD} and θ_{CD} are the scattering angles of the protons detected in the FD and in the CD respectively. The term on the right hand side of Eq. 4.5 is a constant for a certain beam energy.

$$\tan(\theta_{FD}) \cdot \tan(\theta_{CD}) = \frac{1}{\gamma^2} \quad (4.5)$$

The selection of elastically scattered protons is illustrated with data from March 1995 at 750 MeV in Fig. 4.13(a) and with data from April 1996 at 650 MeV in Fig. 4.13(b). In both figures, the product $\tan(\theta_1) \cdot \tan(\theta_2)$ is shown. The points show real data and the solid lines show the results of full Monte Carlo simulations. The improved angular resolution using the new central $\Delta E_1/\Delta E_2$ detector is clearly seen comparing Fig. 4.13(a) and Fig. 4.13(b). The number of elastically scattered protons for each beam energy and run period is extracted by making a cut on each side of the peak formed by the product $\tan(\theta_1) \cdot \tan(\theta_2)$. The small background still present under the peak is subtracted using a linear fit to the background on both sides of the peak.

The two main sources of background in the selected samples of elastically scattered protons come from the reactions $pp \rightarrow pp\pi^0$ and $pp \rightarrow pn\pi^+$. If one of the protons from the $pp \rightarrow pp\pi^0$ reaction ends up in the FD and the other in the CD, the event is similar to an elastic scattering event. The opening angle of the two protons from the $pp \rightarrow pp\pi^0$ reaction is however always lower than 75 degrees whereas the opening angle of the elastically scattered protons is always higher than 80 degrees at the energies studied in this thesis. With a cut on the opening angle of the protons, almost all of the background from the $pp \rightarrow pp\pi^0$ reaction can therefore be discarded. If the proton from the $pp \rightarrow pn\pi^+$ is detected in the FD and the positive pion is detected in the CD, the event can be mistaken for an elastic scattering event. The acceptance is however two orders of magnitude lower than the acceptance to detect the two protons from elastic scattering at all beam energies studied in this thesis. The small background from the $pp \rightarrow pn\pi^+$ reaction that remains in the final samples of elastically scattered protons is evenly distributed in the region under the peaks in histograms such as those shown in Fig. 4.13.

4.8.2 Calculation of the integrated luminosities

The integrated luminosity at each beam energy and run period is calculated using Eq. 4.6, where N_{pp} is the measured number of elastically

(a) Data at 750 MeV from March 1995 (b) Data at 650 MeV from April 1996.

Figure 4.13. The selection of elastically scattered protons. The points show real data and the solid lines show the results of full Monte Carlo simulations.

scattered protons, P_{pp} is the prescaling factor of the trigger used to select the normalization events, E_{pp} is the efficiency to reconstruct the elastic scattering events and σ_{pp} is the integrated differential cross section in the selected angular region.

$$L = \frac{N_{pp} P_{pp}}{\sigma_{pp} E_{pp}}. \quad (4.6)$$

The efficiency includes the event reconstruction efficiency and the trigger efficiency. The event reconstruction efficiency for each run and beam energy is estimated from Monte Carlo simulations. In doing this, the shape of the differential cross section in the selected angular region must be correctly implemented in the Monte Carlo simulation. The elastic scattering events are weighted in FOWL following a parameterization from Ryan et al. [49]. The distributions in scattering angle for the protons detected in the FD are shown in Fig. 4.14(a) for data at 650 MeV from September 1996 and in Fig. 4.14(b) for data at 775 MeV from April 1996. The points show experimental data and the solid lines show the results of full Monte Carlo simulations. The agreement between experimental data and Monte Carlo data is of similar quality at all other energies studied in this thesis. The event reconstruction efficiency at each energy is obtained by dividing the acceptance obtained from the full Monte Carlo simulation

(a) Data at 650 MeV from September 1996 (b) Data at 775 MeV from April 1996.

Figure 4.14. The scattering angles of the elastically scattered protons detected in the FD. The points show real data and the solid lines show the results of full Monte Carlo simulations.

with the detection acceptance obtained from FOWL.

The efficiency of the new central $\Delta E_1/\Delta E_2$ detector is checked in particular. The broken elements can easily be discarded in the analysis. However, the many broken elements could indicate that some elements were working but at reduced efficiency, thus reducing the efficiency of the whole CFB detector. This is further discussed in section 4.9.5. In March 1995 and April 1996, the integrated luminosities obtained using the right and left side of the CD differ by less than 2 percent. For the runs at 650 MeV and 775 MeV in April 1996 as well as for all the following runs periods, only the right side of the CD is used to normalize the data since the horizontal plane of the left CFB detector contained more broken element than the horizontal plane of the right CFB detector. In particular, only half of the horizontal plane of the right CFB detector is used to normalize the data in September 1996.

To make sure that the extracted luminosity is independent on the trigger used to select the normalization events, several different triggers were tried in the analysis but no significant deviations could be found. The trigger efficiencies of the two triggers used to select the elastic scattering events are discussed in section 4.9.3.

Table 4.3. The integrated luminosities for all runs and beam energies.

Run	T_p (MeV)	L_{int} (nb $^{-1}$)
Mar95	725	72
Mar95	750	56
Apr96	650	101
Apr96	750	256
Apr96	775	115
Sep96	650	107
Apr97	650	125
Mar98	680	150

The differential cross sections needed to calculate the integrated cross sections in the selected angular region are taken from R. A. Arndt et al., who have fitted the world data on NN elastic scattering using a partial-wave analysis. Three energy dependent solutions are published by the group, SM94 [50], SM97 [51] and SP00 [52]. The most recent solution, SP00, covers an energy range from threshold up to a laboratory kinetic energy of 3.0 GeV. In particular, the solution includes the precision measurement on the unpolarized elastic proton-proton differential cross sections from the EDDA collaboration [53]. The interactive SAID [54] program is used to extract the differential cross sections at the five beam energies studied in this thesis. The integrated luminosities for all runs and beam energies are presented in table 4.3.

The luminosity can be calculated from the integrated luminosity dividing it by the time of the data taking. As an example, the luminosity during the run at 650 MeV in April 1996 was found to be $1.4 \cdot 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$ with this method. This value can be compared to what is obtained directly from the target thickness and the beam current. The beam current was on average 7.6 mA during the run and the target thickness approximately $1.2 \cdot 10^{14} \text{ cm}^{-2}$. This gives a luminosity of $5.5 \cdot 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$ which is almost four times higher than the value obtained from the integrated luminosity. The reason for the discrepancy is probably due to the uncertainty in the actual target thickness. The lower value, which is used in the normalization procedure, is however consistent with an earlier measurement from March 1995 [28].

4.9 Efficiencies and Errors

The final goal of the analysis is to calculate the total cross sections for the two-pion production reactions studied in this thesis. In order to do this, the efficiencies to detect, reconstruct and identify the events have to be known. The geometrical acceptance, the detection acceptance and the reconstruction efficiency are estimated from Monte Carlo simulations. The trigger efficiencies are extracted from a systematic study of the simple triggers that make up the more complicated physics triggers. Monte Carlo simulations describe the selection of positive pions with the delayed pulse technique well, but overestimate the total efficiency by about 12 percent. The total efficiency of the delayed pulse technique is therefore measured using positive pions from the reaction $pp \rightarrow pn\pi^+$. Due to the many broken elements in the new central $\Delta E_1/\Delta E_2$ detector, the efficiency of this detector is checked experimentally using elastically scattered protons. The errors introduced in the various steps of the analysis are discussed in the last section of this chapter.

4.9.1 Acceptance and event reconstruction efficiency

The overall acceptance to detect and reconstruct the two-pion production reactions consists of three parts, the geometrical acceptance, the detection acceptance and the event reconstruction efficiency. The geometrical acceptance describes how much of the total solid angle that is covered by the detector. The detection acceptance refers to the number of events, with the required number of detected particles, that are expected to fall within the geometrical acceptance. The detection acceptance therefore depends on the reaction in question. The event reconstruction efficiency has to be included since not all events that remain after taking the detection acceptance into account, can be reconstructed and identified. An event can be discarded in the event reconstruction for several reasons, e.g. a particle which does not give a hit in all the layers of the detector until it stops is discarded in the track reconstruction and a particle which undergoes a nuclear interaction in the detector material may get an incorrect kinetic energy in the energy reconstruction.

The overall acceptance for the total cross section measurement is calculated from the number of events that remain after all cuts have been performed in the analysis divided by the number of events originally gen-

erated in FOWL. For the $pp \rightarrow pp\pi^+\pi^-$ reaction the overall acceptance increases with beam energy whereas for the $pp \rightarrow pp\pi^0\pi^0$ and $pp \rightarrow pn\pi^+\pi^0$ reactions, the overall acceptance decreases with beam energy.

The events are originally generated according to phase space in FOWL. However, when the overall acceptance is calculated, final state interaction between the nucleons must be included in the simulations. Final state interaction, and how it is implemented in the Monte Carlo simulations, is further discussed in the following section.

4.9.2 Final state interaction

The product of the eigenvalues for the isospin operator, the space operator and the spin operator must be odd for the NN-pair since the total wave function for a system of spin-1/2 particles must be antisymmetric. The eigenvalue of the space operator is 1 when the angular momentum is even and -1 when the angular momentum is odd. The isospin of a proton-neutron pair can be either one or zero. For a proton pair the isospin can only be one. Assuming that S-wave scattering dominates close to threshold, the angular momentum is zero. It then follows that the proton pair must be in a spin-singlet state whereas the proton-neutron pair can be in either a spin-singlet or a spin-triplet state.

The events in the Monte Carlo simulation are generated according to phase space. The final state interaction is implemented in the event generation by weighting each event with the square of the scattering-wave function. Three types of final state interactions are implemented in the event generation, spin-triplet final state interaction, spin-singlet final state interaction with Coulomb interaction and spin-singlet final state interaction without Coulomb interaction. Two parameterizations of the square of the scattering-wave function are included [55, 56]. Both parameterizations take the scattering-wave function from the Paris nucleon-nucleon potential solved close to its peak at a radius of approximately 1 fm. The two parameterizations describe the effects of final state interaction well at all energies studied in this thesis.

The effect of the attractive spin-singlet final state interaction can be seen in several kinematical distributions, e.g. in the proton-proton invariant mass distribution which is modified from phase space by an enhancement at low proton invariant masses and in the scattering angle distribution of the protons which is modified from phase space by an en-

Figure 4.15. The effects of the proton-proton final state interaction for the $pp \rightarrow pp\pi^+\pi^-$ reaction at 650 MeV. The points show real data. The solid and the dashed lines show the results of full Monte Carlo simulations with and without final state interaction included.

hancement at lower scattering angles. As a result of the attractive final state interaction, some protons are lost in the beam pipe thus decreasing the detection acceptance for the $pp \rightarrow pp\pi^+\pi^-$ and $pp \rightarrow pp\pi^0\pi^0$ reactions. The proton-proton invariant mass distribution for the $pp \rightarrow pp\pi^+\pi^-$ reaction at 650 MeV is shown in Fig. 4.15(a) and the distribution in proton scattering angle for the same reaction and energy is shown in Fig. 4.15(b). The points show data and the solid and dashed lines show the results of full Monte Carlo simulations with and without final state interaction included. The distributions are clearly better described by the Monte Carlo which includes final state interaction.

The proton-proton invariant mass distribution for the $pp \rightarrow pp\pi^0\pi^0$ reaction at 750 MeV is shown in Fig. 4.16(a) and the distribution in scattering angle for the same reaction and energy is shown in Fig. 4.16(b). Again, the distributions are better described by the Monte Carlo which includes final state interaction even though the effects are less obvious as compared to the $pp \rightarrow pp\pi^+\pi^-$ reaction at 650 MeV. The available kinetic energy in the centre-of-mass system is however ~ 50 MeV higher for the $pp \rightarrow pp\pi^0\pi^0$ reaction at 750 MeV as compared to the $pp \rightarrow pp\pi^+\pi^-$

Figure 4.16. The effects of the proton-proton final state interaction for the $pp \rightarrow pp\pi^0\pi^0$ reaction at 750 MeV. The points show real data. The solid and the dashed lines show the results of full Monte Carlo simulations with and without final state interaction included.

reaction at 650 MeV, which indicates that the effects of final state interaction should be less important in the kinematical distributions shown in Fig. 4.16. In addition, the sample of selected $pp \rightarrow pp\pi^0\pi^0$ events still contains background from the $pp \rightarrow pp\pi^0$ reaction which makes the effects of final state interaction more difficult to study experimentally.

The effects of the final state interaction between the nucleons for the $pp \rightarrow pn\pi^+\pi^0$ reaction are more difficult to study experimentally due to bad statistics and the fact that the final distributions are contaminated by events from the $pp \rightarrow d\pi^+\pi^0$ reaction. Fortunately, the effects of final state interaction are less important when calculating the detection acceptance for this reaction since the neutron is not detected in the experiment. Nevertheless, the detection acceptance is compensated for the proton-neutron final state interaction. The total detection acceptance is calculated from a weighted mean of the detection acceptance obtained using spin-singlet final state interaction without Coulomb interaction and spin-triplet final state interaction in the Monte Carlo simulations.

4.9.3 Trigger efficiencies

In the analysis, the efficiencies of the different triggers have to be known to be able to calculate the luminosities during the different experimental runs and, in the end, the total cross sections of the two-pion production reactions. Preferably, the triggers should pick out events from only the interesting reactions. In reality this turns out to be difficult and the triggers are usually a compromise between selectivity and efficiency. If a trigger is very selective, i.e. almost all of the events picked out by the trigger come from the wanted reaction, the efficiency tends to be low. On the other hand, a very efficient trigger which does not put strong conditions on the events, may select a lot of background events that give similar signatures in the detector instead.

The efficiency of a primary trigger is defined as the ratio between the number of events for which the trigger is set and the number of events for which the trigger condition is fulfilled. The efficiency of a secondary trigger consists of two parts. The first part is the efficiency of the secondary trigger to be set when all included primary triggers are set. The second part is the product of the efficiencies for each included primary trigger. The efficiency of a secondary trigger can be measured in the analysis providing that all included primary triggers were connected to the DAS during the experiment.

Triggers to pick out $pp \rightarrow pp\pi^+\pi^-$ events

The triggers used to pick out the events with at least three charged tracks in the FD were secondary triggers formed by combining several primary triggers as described in section 3.6. Even though several triggers were tried, only TWR32 and TWJ12 were used in the analysis. As mentioned in the previous section, the efficiency of a secondary trigger consists of two parts. The first part of the efficiency, namely the efficiency of the secondary trigger to be set when all included primary triggers are set, was on average 99.7 percent for both TWR32 and TWJ12.

The efficiency for each of the five primary triggers included in TWR32 and TWJ12 is measured in a similar way in the analysis. As an example, consider the primary trigger TJ3. This trigger should be set for all events with three hits in the third layer of the FHD for which the TDC signals from the three hits overlap a sufficiently long time to form a coincidence signal. The first step in finding the efficiency of TJ3 is therefore to extract

the limits of the allowed time window. This is done by picking out events with the prescaled version of TJ3. All events with exactly three hits in the third layer of the FHD are selected. By definition, the three hits in the FHD must have formed a coincidence signal. The time limits are extracted from a histogram where the maximum time difference between any of the hits is plotted.

The second step in finding the efficiency of TJ3 is to pick out events with a prescaled trigger which is independent of TJ3, e.g. TR3. The events are reconstructed and those which have at least three hits in the third layer of the FHD within the allowed time window are selected. The efficiency of TJ3 is obtained by dividing the number of selected events for which TJ3 is set with the total number of selected events.

The same procedure as described above is used to extract the efficiency for each of the four remaining primary triggers. The total efficiencies of the three-particle triggers were ~ 93 percent for all run periods. As mentioned in section 3.6, the trigger TWR32 was changed by mistake during the run in April 1996 to include TJ1 instead of TJ3. Fortunately, the effect on the trigger efficiency was less than 1 percent.

Triggers to pick out $pp \rightarrow pp\pi^0\pi^0$ and $pp \rightarrow pn\pi^+\pi^0$ events

The efficiencies of the two triggers used to pick out events with at least one gamma in each CsI box are checked in a similar way as the three particle triggers. Each group of crystals in one CsI box can form a coincidence signal with any group of crystals in the opposite CsI box. The first step in finding the efficiency of e.g. T10 is therefore to extract the allowed time windows for all possible combinations of groups from the right and left CsI box in a similar way as described above for the primary trigger TJ3.

The second step in extracting the efficiency of T10 is to select events with the primary trigger T7. This trigger picks out events with at least one hit in the CD. The events with one gamma in each CsI box are kept in the analysis. A loop over all hit groups is performed to find if there exist at least one group combination for which the two signals are within the allowed time window. If such a combination is found, the event is selected. The efficiency of T10 is obtained by dividing the number of selected events for which T10 is set with the total number of selected events.

The efficiency of T14 which was used during the run in March 1995 was close to 90 percent, whereas the efficiency of T10 used during all following runs was only ~ 50 percent. The reason for the low efficiency of T10 is that the time overlap between the signals from the left and right trigger groups in many cases were too short to produce a coincidence signal in the trigger TDC. The result was that T10 could start the DAS, but the trigger signal was not written to tape. Unfortunately, the efficiency of T10 also varied with the dead time of the DAS, which led to a rather large error in the trigger efficiency for T10. This is further discussed in section 4.9.6. For some run periods, the trigger T10 was connected to a prescaler TDC even though it was not prescaled. The time window of the prescaler TDC was more generous than the time window of the normal trigger TDC. For the run periods where the prescaler TDC could be used, the efficiency of T10 was ~ 65 percent.

Triggers to pick out $pp \rightarrow pp$ events

The normalization triggers T1 and T3 should be set for all events with at least one charged track in the FD. The efficiencies of T1 and T3 are checked using events picked out by a trigger which is independent of the FD. The primary trigger T5 picks out events with one charged track in the CD. This trigger could in fact be used as a main trigger to pick out elastically scattered protons instead of T1 and T3. The events picked out by T5 are reconstructed and those which have one charged track in the FD are selected. The efficiencies of T1 and T3 are obtained by dividing the number of selected events for which T1 and T3 are set with the total number of selected events. The efficiencies of T1 and T3 were ~ 99.5 percent for all run periods

4.9.4 The efficiency of the delayed pulse technique

Monte Carlo simulations describe the selection of positive pions using the delayed pulses from the decay of the muons well, but overestimate the total efficiency. The total efficiency is therefore measured using positive pions from the $pp \rightarrow pn\pi^+$ reaction at 360 MeV. The distribution in scattering angle for the $pp \rightarrow pn\pi^+$ is similar to the distribution in scattering angle for the positive pions from the $pp \rightarrow pp\pi^+\pi^-$ reaction at 650 and 680 MeV. Another possibility would be to use the $pp \rightarrow d\pi^+$ reaction which is easier to identify. However, the distribution in pion scattering angle only

covers a part of the available angular region of the FD.

The distributions in scattering angle for the positive pions identified without (solid line) and with (dashed line) the requirement of a delayed pulse from the muon decay are shown in Fig. 4.17(a). To check the angular efficiency of the delayed pulse identification, the quota of the two distributions is shown in Fig. 4.17(b). The efficiency is almost constant in the angular region between 7 and 20 degrees. At lower and higher scattering angles, edge effect are clearly seen. Monte Carlo simulations are however able to describe the angular efficiency of the delayed pulse identification well, as illustrated in Fig. 4.17(c), where positive pions identified with the delayed pulse technique from the $pp \rightarrow pp\pi^+\pi^-$ reaction at 680 MeV are shown (points) together with the result of a full Monte Carlo simulation (solid line). The similarity in the scattering angle distributions for positive pions from the $pp \rightarrow pn\pi^+$ reaction and the $pp \rightarrow pp\pi^+\pi^-$ reaction can be seen comparing Fig. 4.17(a) and Fig. 4.17(c). The delayed-pulse times for all particles identified as positive pions with the delayed pulse technique from the $pp \rightarrow pn\pi^+$ reaction at 360 MeV is shown in Fig. 4.17(d). A fit to the slope gives a value of 2337 ns for the mean life time of positive muons, in reasonable agreement with the reference value of 2197 ns taken from the Particle Data Group [48].

The total efficiency to identify positive pions with the delayed pulse technique is estimated from Monte Carlo simulations to be ~ 73.5 percent, whereas the measured total efficiency using positive pions from the $pp \rightarrow pn\pi^+$ reaction at 360 MeV is ~ 65 percent. The event reconstruction efficiency obtained from Monte Carlo simulations where delayed pulse identification of the positive pions is required therefore has to be modified with a correction factor of 12 percent. The most important reason for the discrepancy between experiment and Monte Carlo is probably the lack of background events in the Monte Carlo simulations. Delayed pulses from the muons can be discarded by veto signals caused by other particles in the experimental data, thus decreasing the measured efficiency to identify positive pions with the delayed pulse technique.

4.9.5 The efficiency of the central $\Delta E_1/\Delta E_2$ detector

Since the protons detected in the CD are required to have hits in all layers of the central $\Delta E_1/\Delta E_2$ detector, an inefficiency in this detector could influence the extracted number of elastic scattering events. The efficiency

(a) Experimental data at 360 MeV showing events from the $pp \rightarrow pn\pi^+$ reaction with (dashed line) and without (solid line) the requirement of a delayed pulse from the decay of the muon.

(b) The scattering angle distribution of positive pions identified with the delayed pulse technique divided by the scattering angle distribution of positive pions identified without the delayed pulse technique from the $pp \rightarrow pn\pi^+$ reaction at 360 MeV.

(c) Positive pions identified with the delayed pulse technique from the $pp \rightarrow pp\pi^+\pi^-$ reaction at 680 MeV. The points show experimental data and the solid line shows the result of a full Monte Carlo simulation.

(d) The delayed-pulse times for all particles identified as positive pions with the delayed pulse technique from the $pp \rightarrow pn\pi^+$ reaction at 360 MeV. A fit to the slope gives a value of 2337 ns for the mean life time of positive muons.

Figure 4.17. The angular and total efficiency of the delayed pulse identification of positive pions together with the measured mean life time of the muon.

of the central $\Delta E_1/\Delta E_2$ detector can be estimated comparing the number of elastic scattering events found requiring only a hit in the CsI box with the number of events found if hits in all layers of the central $\Delta E_1/\Delta E_2$ detector are required in addition. The efficiency of the right side of the CFB detector as well as the efficiencies of both sides of the CDE detector were found to be above 99 percent. The result for the CDE detector is in agreement with an earlier measurement from 1993 [25].

4.9.6 Errors

The different steps in the analysis introduce errors which influence the total error of the final result in the analysis, i.e. the total cross sections of the two-pion productions reactions. The total errors consist of both statistical and systematic errors. The statistical errors differ for each reaction and beam energy whereas the systematic errors are similar for the different reactions and beam energies. The error in the beam energy is estimated to be below 0.5 MeV (cf. section 4.2.2) and is neglected in the analysis.

The statistical errors are given by the inverse square root of the number of events used to calculate the total cross sections. For the $pp \rightarrow pp\pi^+\pi^-$ reaction, the statistical errors are of the order of 5 percent at the two energies studied in this thesis. For the $pp \rightarrow pp\pi^0\pi^0$ reaction, the statistical errors vary between 2 and 18 percent at the four energies studied in this thesis. For the $pp \rightarrow pn\pi^+\pi^0$ reaction, the statistical errors vary between 6 and 12 percent at the three energies studied in this thesis. The statistical errors for each reaction and beam energy are shown in appendix A.

The errors in the efficiencies of the triggers used to select the two-pion production events in the experiments contribute to the total error in the efficiency to detect the reactions. The errors in the efficiencies of the triggers are estimated by using different triggers to pick out the events used to measure the trigger efficiencies and by varying the limits of the allowed time windows of the trigger TDCs. The errors in the efficiencies are estimated to be below 5 percent for the two triggers used to select the $pp \rightarrow pp\pi^+\pi^-$ events in the experiment. The error in the efficiency of the trigger used to select the $pp \rightarrow pp\pi^0\pi^0$ events in March 1995, T14, is also estimated to be below 5 percent. The error in the efficiency of T10 which was used during all other runs is unfortunately considerably larger. The

number of events on the original tapes from the experiments for which the trigger T10 is likely to have started the DAS was about the same as for the trigger T14. However, in only 50 to 65 percent of the cases when T10 started the DAS was a coincidence signal formed in the trigger TDC. The efficiency to form the coincidence signal also varied with the dead time of the DAS. Taking this into account, the error in the efficiency of T10 is estimated to be close to 15 percent. The triggers used to select the normalization events are simpler than the triggers used to select the two-pion production reactions. The errors in the efficiencies of the two normalization triggers used in the analysis are estimated to be below 1.5 percent.

The determination of the overall acceptance from Monte Carlo simulations introduce an error in the total efficiency to detect the reactions. The biggest error in the overall acceptance comes from determining the detection acceptance, since this strongly depends on a correct description of the final state interaction between the outgoing nucleons. The error in the detection acceptance is estimated by varying the strength of the final state interaction in the Monte Carlo simulations when comparing the kinematical distributions obtained from Monte Carlo with those obtained from experimental data. In order to check that the parameterization of the square of the scattering-wave function does not change the results, two different parameterizations are included in the Monte Carlo simulations. The error in the detection acceptance is different for each reaction and beam energy, mainly due to the available statistics and the amount of background in the experimental kinematical distributions which influence the comparison with Monte Carlo generated distributions. The event reconstruction efficiency including broken elements and misalignment of the detectors also introduces an error. The total error from the overall acceptance and the event reconstruction is below 10 percent for each reaction and beam energy studied in this thesis.

The delayed pulse identification of positive pions introduces an additional error in the event reconstruction efficiency for the $pp \rightarrow pp\pi^+\pi^-$ and $pp \rightarrow pn\pi^+\pi^0$ reactions. The total efficiency estimated from Monte Carlo simulations is ~ 12 percent higher than the total efficiency obtained from experimental data. Since the discrepancy between experimental results and Monte Carlo simulations is not fully understood, a total error in the efficiency to identify positive pions of 12 percent is assumed in the analysis (cf. section 4.9.4).

The data used to extract the integrated luminosities for each run are recorded in parallel and analysed with the same code as the other reactions. The integrated luminosities therefore suffer from similar systematic errors as the other reactions. The errors in the reference data taken from the SAID data base are assumed to be less than 5 percent since the partial wave analysis include the new high precision EDDA data which, according to the EDDA collaboration, have a 5 percent absolute normalization error. The error in acceptance and event reconstruction efficiency, including the efficiency of the central $\Delta E_1/\Delta E_2$ detector is estimated to be less than 5 percent from Monte Carlo simulations. An additional 5 percent error comes from the background subtraction in the elastic scattering data. In total, the overall error in the normalization is around 10 percent for all run periods used in this thesis.

The background subtraction introduces an error since it is difficult to estimate the exact shape of the background in the final distributions of the selected events. The error is estimated by varying the contribution from different background reactions in the Monte Carlo simulations. The error in subtracting the background is different for each reaction and beam energy. For the $pp \rightarrow pp\pi^+\pi^-$ reaction, the only remaining background in the final event sample comes from the $pp \rightarrow pn\pi^+$ reaction and the error in subtracting that background is estimated to be 8 and 10 percent at 650 and 680 MeV respectively. For the $pp \rightarrow pp\pi^0\pi^0$ reaction, the background from the $pp \rightarrow pp\pi^0$ reaction is more difficult to handle and the error varies between 11 and 13 percent at the four beam energies studied in this thesis. For the $pp \rightarrow pn\pi^+\pi^0$ reaction, the background from one-pion production reactions is small. Unfortunately, the selected event samples contain events from both the $pp \rightarrow pn\pi^+\pi^0$ and the $pp \rightarrow d\pi^+\pi^0$ reactions. The error in estimating the contribution from the later reaction varies between 14 and 20 percent at the three beam energies studied in this thesis.

The total systematic errors for each reaction and beam energy are shown in appendix A. The total errors, including both statistical and systematic errors, are close to 22 percent for the $pp \rightarrow pp\pi^+\pi^-$ reaction, between 16 and 30 percent for the $pp \rightarrow pp\pi^0\pi^0$ reaction and between 27 and 32 percent for the $pp \rightarrow pn\pi^+\pi^0$ reaction at the energies studied in this thesis.

CHAPTER 5

Results and conclusions

The total cross sections for the $pp \rightarrow pp\pi^+\pi^-$, the $pp \rightarrow pp\pi^0\pi^0$ and the $pp \rightarrow pn\pi^+\pi^0$ reactions have been measured in the near threshold energy region using the PROMICE/WASA detector and an internal cluster gas-jet target at the CELSIUS storage ring. Some of the more important parts of the analysis were the identification of neutral pions from the invariant mass of the decay gammas, the identification of positive pions with the delayed pulse technique and the use of Monte Carlo simulations to understand the detector response.

$$\sigma = \frac{N}{A \cdot L} \quad (5.1)$$

The total cross sections are calculated according to Eq. 5.1, where N is the number of selected events, A is the overall acceptance and L is the integrated luminosity. The overall acceptance includes the detection acceptance, the event reconstruction efficiency, the trigger efficiency and, when used, the efficiency of the delayed pulse identification of positive pions. In this chapter, the total cross sections are compared to the previously existing data and the theoretical predictions from the model discussed in section 2.1.2. A few kinematical distributions are shown for each reaction together with the results from full Monte Carlo simulations including final state interaction between the nucleons. The experimental kinematical distributions are shown with statistical errors only. The total cross sections together with the statistical and systematic errors for each reaction and energy are given in appendix A.

5.1 The $pp \rightarrow pp\pi^+\pi^-$ reaction

The delayed pulse identification of positive pions turned out to be necessary for the $pp \rightarrow pp\pi^+\pi^-$ reaction in order to discard the background from neutral one-pion production. Since all but one of the four particles in the final state were measured in the experiments, the $pp \rightarrow pp\pi^+\pi^-$ events could be completely reconstructed in the analysis. The data at 650 MeV were collected during three separate run periods, April 1996, September 1996 and April 1997. The total cross sections at 650 MeV calculated from each of the run periods agree within 1.5 percent. Furthermore, the total cross section for the $pp \rightarrow pp\pi^+\pi^-$ reaction at 750 MeV from W. Brodowski [1] also agree with the results in this thesis, provided that the total cross section follow phase space in the near threshold energy region. The analysis performed by W. Brodowski is, to a large extent, independent from the analysis presented in this thesis.

5.1.1 The total cross section

The total cross sections for the $pp \rightarrow pp\pi^+\pi^-$ reaction at 650 and 680 MeV are shown in Fig. 5.1 together with the previously existing data in the intermediate and near threshold energy region discussed in section 2.2. The solid and dashed curves show theoretical predictions from the model discussed in section 2.1.2. The dotted curve shows a phase space fit using only the new data from the PROMICE/WASA collaboration. The total cross section from W. Brodowski at 750 MeV is also included in the figure [1]. The total cross sections added by the PROMICE/WASA collaboration in the near threshold energy region are considerably lower than what is expected from the previously existing measurements, with the exception of the total cross section from Cverna et al. at 800 MeV. The PROMICE/WASA data agree with the theoretical prediction from Alvarez-Ruso, Oset and Hernández. However, the theoretical calculations do not include final state interaction between the protons. Including final state interaction in the model would increase the total cross section close to threshold [15]. The kinematical distributions are well described by phase space Monte Carlo with proton-proton final state interaction included. This is expected if the production mechanism is completely dominated by the $N^*(1440)$ resonance with the subsequent decay channel $N^*(1440) \rightarrow N(\pi\pi)_{S-wave}^{T=0}$.

Figure 5.1. The total cross sections for the $pp \rightarrow pp\pi^+\pi^-$ reaction from the PROMICE/WASA collaboration shown together with the previously existing data in the intermediate and near threshold energy region discussed in section 2.2 and the theoretical predictions from the model discussed in section 2.1.2. The dotted curve shows a phase space fit using only the new data from the PROMICE/WASA collaboration.

5.1.2 Kinematical distributions

The selected event samples for the $pp \rightarrow pp\pi^+\pi^-$ reaction contain only a small amount of background events from the $pp \rightarrow pn\pi^+$ reaction. The distributions in scattering angle and kinetic energy for protons from the $pp \rightarrow pp\pi^+\pi^-$ reaction at 650 MeV are shown in Figs. 5.2(a)(b). The corresponding distributions for positive pions from the $pp \rightarrow pp\pi^+\pi^-$ reaction at 680 MeV are shown in Figs. 5.2(c)(d). The points show experimental data and the shaded histograms show the results of full phase space Monte Carlo simulations including final state interaction between the two

(a) The scattering angle of the protons at 650 MeV.

(b) The kinetic energy of the protons at 650 MeV.

(c) The scattering angle of the positive pions at 680 MeV.

(d) The kinetic energy of the protons at 680 MeV.

Figure 5.2. A few kinematical distributions for the $pp \rightarrow pp\pi^+\pi^-$ reaction at 650 and 680 MeV. The points show experimental data and the shaded histograms show the results of full phase space Monte Carlo simulations including final state interaction between the protons.

(a) The missing mass distribution of the two protons at 650 MeV.

(b) The missing mass distribution of the two protons at 680 MeV.

Figure 5.3. Missing mass distributions of the two protons for the $pp \rightarrow pp\pi^+\pi^-$ reaction at 650 and 680 MeV. The points show experimental data and the shaded histograms show the results of full phase space Monte Carlo simulations including final state interaction between the protons.

protons. The agreement between the experimental data and the Monte Carlo generated data is reasonable at both energies. In particular, the distribution in scattering angle for the protons can only be described by Monte Carlo which includes final state interaction between the protons.

The missing mass distributions of the two protons for the $pp \rightarrow pp\pi^+\pi^-$ reaction are shown in Figs. 5.3(a)(b) for data at 650 and 680 MeV respectively. A slight shift towards higher missing masses as compared to phase space is indicated at 680 MeV in Fig. 5.3(b). The missing mass distribution of the two protons is equivalent to the invariant mass distribution of the two pions. The number of events at the two energies studied in this thesis are not sufficient to make any statements about the $\pi\pi$ -interaction based on kinematical distributions. However, the missing mass distributions of the two protons at 750 MeV clearly deviate from phase space as shown by W. Brodowski [1]. The excess energy in the CMS for the $pp \rightarrow pp\pi^+\pi^-$ reaction is ~ 65 MeV at a beam energy of 750 MeV and ~ 35 MeV at a beam energy of 680 MeV.

5.2 The $pp \rightarrow pp\pi^0\pi^0$ reaction

The selective trigger which was used to pick out the events with one or two neutral pions in the final state together with the low detection acceptance for the $pp \rightarrow pp\pi^0$ reaction, made it possible to measure the total cross sections for the $pp \rightarrow pp\pi^0\pi^0$ reaction. Only the events that passed the kinematical fit procedure were completely reconstructed in the analysis. Data at 750 MeV were collected at two separate run periods, March 1995 and April 1996. The total cross sections calculated from each of the run periods agree within 4.5 percent, despite the fact that the data in April 1996 were collected with the troublesome T10 trigger.

5.2.1 The total cross section

The total cross sections for the $pp \rightarrow pp\pi^0\pi^0$ reaction at 650, 725, 750 and 775 MeV are shown in Fig. 5.4 together with the previously existing data in the intermediate and near threshold energy region discussed in section 2.2. The solid and dashed curves show theoretical predictions from the model discussed in section 2.1.2. The dotted curve shows a phase space fit using only the new data from the PROMICE/WASA collaboration. The PROMICE/WASA data agree with the theoretical prediction from Alvarez-Ruso, Oset and Hernández except for the total cross section at 650 MeV. However, the theoretical calculations do not include final state interaction between the protons. The data point at 650 MeV indicates that the shape of the total cross section near threshold is different from the shape predicted by the model. Including final state interaction between the protons in the model might change the shape and the magnitude of the predicted total cross section. The kinematical distributions are well described by phase space Monte Carlo with proton-proton final state interaction included. This is expected if the same resonance as for the $pp \rightarrow pp\pi^+\pi^-$ reaction dominates the production mechanism.

5.2.2 Kinematical distributions

The event samples which are used to calculate the total cross sections contain a significant amount of background events from the $pp \rightarrow pp\pi^0$ reaction. The event samples selected using the kinematical fit procedure on the other hand, contain only a small amount of background events and are, as a result of the kinematical fit procedure, completely recon-

Figure 5.4. The total cross sections for the $pp \rightarrow pp\pi^0\pi^0$ reaction from the PROMICE/WASA collaboration shown together with the previously existing data in the intermediate and near threshold energy region discussed in section 2.2 and the theoretical predictions from the model discussed in section 2.1.2. The dotted curve shows a phase space fit using only the new data from the PROMICE/WASA collaboration.

structed. The distribution of the relative momentum for protons from the $pp \rightarrow pp\pi^0\pi^0$ reaction at 725 MeV is shown in Fig. 5.5(a). The distribution in kinetic energy for protons from the $pp \rightarrow pp\pi^0\pi^0$ reaction at 750 MeV is shown in Fig. 5.5(b). The distributions in opening angle and planarity for protons from the same reaction at 775 MeV are shown in Figs. 5.5(c)(d). In all figures the points show experimental data and the shaded histograms show the results of full phase space Monte Carlo simulations including final state interaction between the protons. In particular, the distribution of the proton-proton relative momentum can only be described by Monte Carlo which includes final state interaction between

(a) The proton-proton relative momentum at 725 MeV.

(b) The kinetic energy of the protons at 750 MeV.

(c) The proton-proton opening angle at 775 MeV.

(d) The planarity of the protons at 775 MeV.

Figure 5.5. A few kinematical distributions for the $pp \rightarrow pp\pi^0\pi^0$ reaction at 725, 750 and 775 MeV. The points show experimental data and the shaded histograms show the results of full phase space Monte Carlo simulations including final state interaction between the protons.

the protons. The low statistics at 650 MeV made it difficult to study kinematical distributions at that energy.

5.3 The $pp \rightarrow pn\pi^+\pi^0$ reaction

For the $pp \rightarrow pn\pi^+\pi^0$ reaction, the background from neutral one-pion production could be removed with a cut on the missing mass of the proton and the two pions. However, the delayed pulse identification of the positive pions was necessary to discard the background from neutral two-pion production instead. The events from the $pp \rightarrow pn\pi^+\pi^0$ reaction are completely reconstructed in the analysis since all particles except the neutron are measured in the experiment. Data at 750 MeV were collected at two separate run periods, March 1995 and April 1996. The total cross sections calculated from each of the run periods agree within 15 percent. The reason for the larger discrepancy between the different measurements of the total cross section for the $pp \rightarrow pn\pi^+\pi^0$ reaction as compared to the $pp \rightarrow pp\pi^0\pi^0$ reaction, is the more difficult background subtraction in case of the former reaction.

5.3.1 The total cross section

The total cross sections for the $pp \rightarrow pn\pi^+\pi^0$ reaction at 725, 750 and 775 MeV are shown in Fig. 5.6 together with the previously existing data in the intermediate and near threshold energy region discussed in section 2.2. The solid and dashed curves show theoretical predictions from the model discussed in section 2.1.2. The dotted curve shows a phase space fit using only the new data from the PROMICE/WASA collaboration. For this reaction, the predictions from the model by Alvarez-Ruso, Oset and Hernández do not agree with the experimental data added by the PROMICE/WASA collaboration. The predicted total cross section is considerably smaller than the experimental total cross section. The reason for the small predicted total cross section near threshold is that the dominating production mechanism in the model, $N^*(1440) \rightarrow N(\pi\pi)_{S-wave}^{T=0}$, is forbidden by isospin conservation for the $pp \rightarrow pn\pi^+\pi^0$ reaction. The new data from the PROMICE/WASA collaboration show that other processes must give large contributions to the total cross section for this reaction channel near threshold.

Figure 5.6. The total cross sections for the $pp \rightarrow pn\pi^+\pi^0$ reaction from the PROMICE/WASA collaboration shown together with the previously existing data in the intermediate and near threshold energy region discussed in section 2.2 and the theoretical predictions from the model discussed in section 2.1.2. The dotted curve shows a phase space fit using only the new data from the PROMICE/WASA collaboration.

5.3.2 Kinematical distributions

The available statistics is not sufficient to plot any interesting kinematical distributions for the $pp \rightarrow pn\pi^+\pi^0$ reaction. In addition, the final event samples still contain a significant amount of background events from the $pp \rightarrow d\pi^+\pi^0$ reaction. The Monte Carlo simulations for this reaction channel must therefore include both the $pp \rightarrow pn\pi^+\pi^0$ and the $pp \rightarrow d\pi^+\pi^0$ reactions to be able to describe the experimental distributions, as discussed in section 4.7.3. The distributions in kinetic energy and scattering angle for positive pions from the $pp \rightarrow pn\pi^+\pi^0$ reaction at 750 MeV are shown

Figure 5.7. A few kinematical distributions for the $pp \rightarrow pn\pi^+\pi^0$ reaction at 750 MeV. The points show experimental data and the shaded histograms show the results of full phase space Monte Carlo simulations including both the $pp \rightarrow pn\pi^+\pi^0$ and the $pp \rightarrow d\pi^+\pi^0$ reactions.

in Figs. 5.7(a)(b). The corresponding distributions for neutral pions are shown in Figs. 5.7(c)(d) for the same reaction and energy. The points show experimental data and the shaded histograms show the results of full phase space Monte Carlo simulations including both the $pp \rightarrow pn\pi^+\pi^0$ and the $pp \rightarrow d\pi^+\pi^0$ reactions. The agreement between experimental data and Monte Carlo simulations is of similar quality at the other two energies studied in this thesis.

5.4 Conclusions and outlook

The kinematical distributions for the $pp \rightarrow pp\pi^+\pi^-$ and the $pp \rightarrow pp\pi^0\pi^0$ reactions near threshold are well described by phase space Monte Carlo when proton-proton final state interaction is included. This is consistent with the transition $N^*(1440) \rightarrow N(\pi\pi)_{S-wave}^{T=0}$ as the dominant production mechanism near threshold. The total cross sections for the $pp \rightarrow pp\pi^+\pi^-$ and the $pp \rightarrow pp\pi^0\pi^0$ reactions also agree with the predictions from the model by Alvarez-Ruso, Oset and Hernández, with the exception of the total cross section at 650 MeV for the $pp \rightarrow pp\pi^0\pi^0$ reaction. However, final state interaction between the outgoing nucleons is not included in the calculations. Including final state interaction in the model might change both the shape and the magnitude of the predicted total cross sections near threshold. Also, the total cross section for the $pp \rightarrow pn\pi^+\pi^0$ reaction is considerably larger than the predicted total cross section from the model by Alvarez-Ruso, Oset and Hernández. By comparing the experimental data and the predictions from the model, it is clear that other processes than the transition $N^*(1440) \rightarrow N(\pi\pi)_{S-wave}^{T=0}$ must give large contributions near threshold.

The WASA detector was recently installed at CELSIUS. In this detector, the acceptance for all two-pion production reactions in proton-proton collisions is almost 4π . In addition, the magnetic field inside the superconducting solenoid, together with the mini-drift chamber, will make it possible to separate positive and negative pions. The luminosity using the hydrogen-pellet target is expected to be ~ 100 times the luminosity of the cluster gas-jet target. In total, this will provide excellent opportunities to measure both differential and total cross sections for all two-pion production reactions in proton-proton collisions. In particular, the $\pi\pi$ -interaction can be studied in detail.

APPENDIX A

Cross sections

Table A.1. The total cross sections for the $pp \rightarrow pp\pi^+\pi^-$ reaction at 650 and 680 MeV together with statistical and systematic errors.

Energy (MeV)	Cross section (nb)
	$\sigma \pm e^{stat} \pm e^{syst}$
650	$45 \pm 3 \pm 10$
680	$148 \pm 6 \pm 32$

Table A.2. The total cross sections for the $pp \rightarrow pp\pi^0\pi^0$ reaction at 650, 725, 750 and 775 MeV together with statistical and systematic errors.

Energy (MeV)	Cross section (nb)
	$\sigma \pm e^{stat} \pm e^{syst}$
650	$50 \pm 7 \pm 15$
725	$518 \pm 22 \pm 104$
750	$1038 \pm 25 \pm 158$
775	$1677 \pm 42 \pm 404$

Table A.3. The total cross sections for the $pp \rightarrow pn\pi^+\pi^0$ reaction at 725, 750 and 775 MeV together with statistical and systematic errors.

Energy (MeV)	Cross section (nb)		
	σ	$\pm e^{stat}$	$\pm e^{syst}$
725	831	± 100	± 201
750	1363	± 78	± 260
775	2288	± 224	± 790

Acknowledgements

I have been fortunate to meet many nice people during my time as a PhD student at the Department of Radiation Sciences. It would be impossible to mention everyone who has contributed to this thesis, so if you don't find your name below, this is for you: Thank you!

First of all, I like to thank my supervisor Bo Höistad for his support during my time as PhD student and for helping me in finishing this thesis. I'm particularly grateful to Stina Häggström. Without her help, I probably wouldn't have continued as a PhD student. I don't think that I ever managed to think of a question that she couldn't answer. I also like to thank Hans Calén for a lot of help during my first years of struggle with the analysis code. I'm grateful to Kjell Fransson for his hard work during the experiments. Among other things, he was the only one who knew the secret trick to get the high-voltage system going when it died (If you would ever be in a situation where you had to start a high-voltage system, this is what you must do: 1. pull out a few cables, 2. put them back, 3. try to start, 4. go back to 1.). I'm also grateful to Pia Thörngren-Engblom for proof-reading the thesis and for helpful suggestions on how to improve it. Thanks to Tord Johansson for showing me a program which can be used to remove annoying pixels from pictures. With this program, I could improve the scanned picture of the tracker (you remember that one, don't you? If not, check out page 27).

During my time in the PROMICE/WASA group, I have met many PhD students and postdocs from other universities. Thanks to Jan Greiff for many discussions about the analysis code and, more importantly for both of us I believe, nice squash games. I'm grateful to Wolfram Brodowski and Jens Pätzold for discussions about the analysis and for organizing an excellent workshop in Tübingen. Thanks also to Alfons Khoukaz for a lot of useful suggestions on the analysis and for inviting

me to Münster. We struggled with the T10-problem together (cf. section 3.6). It wasn't fun, but someone had to do it.

Thanks to Carl-Johan Fridén for running the cluster gas-jet target and Dag Reistad for running the CELSIUS ring during the experiments. Both Carl-Johan and Dag were always helpful during as well as after the experiments. I also enjoyed running the cyclotron instead of doing laboratory exercises during one year, although I have to say, when you've seen the first turn, you've seen them all. Thanks to Ib Koersner, Roger Ruber and Stephan Pomp for running the computer systems and, in particular, for making it possible to print with twice the resolution the very same week that I handed in my thesis to the printing office. Thanks also to Stephan Pomp and Anders Gårdestig for providing me with helpful hints and template files in Latex. Some things in Latex are known exclusively on a folklore level. They are passed on from one PhD student to the next in secret meetings.

Petter Sundberg and I shared a room for more than two years time. We talked about a lot of things, sometimes about physics, but mostly about thing going on in the rest of the world. Thanks Petter! It was suddenly quite boring in our room when you left to work for Ericsson. Anders Axelsson and I fought side by side in the laboratory exercises during many years. It was fun working with you Anders! I'm grateful to Maria Gunther-Axelsson for always picking us up before going to lunch. Lunch breaks and coffee breaks are probably the most important parts of a PhD students working day. Like every experienced PhD student, Maria also had her share of Latex and PAW secrets to share.

I'm grateful to all my friends for giving me something else to think about than tape stations. I could always count on you to sing the cyclotron song whenever I felt a bit tired of the whole PhD thing. Finally, I would like to thank my family for a lot of help during the past five years and Eleonora for taking care of me and sharing the bad and the good parts of my time as a PhD student.

References

- [1] W. Brodowski, *Exclusive Measurement of the Reaction $pp \rightarrow pp\pi^+\pi^-$ at CELSIUS and the Search for d'* , PhD thesis, Tübingen University, 2000.
- [2] J. Pätzold, Phd thesis, tübingen university, in preparation.
- [3] M. Taketani, S. Nakamura, M. Sasaki, *Proc. Theor. Phys. (Kyoto)* **6** (1951) 581.
- [4] R. Machleidt, *Advances in Nuclear Physics*, vol. 19, p. 189, Plenum Press, New York, 1989.
- [5] L. G. Dakhno et al., *Sov. J. Nucl. Phys.* **37** (1983) 540.
- [6] J. Bystricky et al., *J. Physique* **48** (1987) 1901.
- [7] J.A. Gómez Tejedor and E. Oset, *Nucl. Phys.* **A 571** (1985) 667.
- [8] J.A. Gómez Tejedor and E. Oset, *Acta Physica Polonica* **B 27** (1996) 3171.
- [9] E. Oset and M.J. Vicente-Vacas, *Nucl. Phys.* **A 446** (1994) 584.
- [10] V. Sossi et al., *Nucl. Phys.* **A 548** (1992) 562.
- [11] G. R. Smith, *Mesons and Light Nuclei'98*, p. 35, 1998.
- [12] L. Alvarez-Ruso, E. Oset, E. Hernández, *Nucl. Phys.* **A 633** (1998) 519.
- [13] S. Hirenzaki et al., *Phys. Rev.* **C 53** (1996) 277.
- [14] L. Alvarez-Ruso, Private communication.

-
- [15] L. Alvarez-Ruso, *Excitation of Baryonic Resonances Induced by Nucleons and Leptons*, PhD thesis, University of Valencia, 1999.
 - [16] F. Shimitzu et al., *Nucl. Phys. A* **386** (1982) 571.
 - [17] J. Stepaniak, Private communication.
 - [18] F. H. Cverna et al., *Phys. Rev. C* **23** (1980) 23.
 - [19] D. C. Brunt et al., *Phys. Rev.* **187** (1969) 1856.
 - [20] TSL Progress Report, 1998-1999.
 - [21] D. Reistad (1997), *Performance and Perspectives on CELSIUS*, TSL Note 97-31.
 - [22] C. Ekström et al., *Nucl. Inst. and Meth. A* **371** (1996) 572.
 - [23] C. Ekström et al., *Nucl. Phys. A* **626** (1997) 405.
 - [24] H. Calen et al., *Nucl. Inst. and Meth. A* **379** (1996) 57.
 - [25] A. Mörtzell, *Neutral pion Production in Proton-Proton Collisions Close to the Kinematical Threshold*, PhD thesis, Uppsala University, 1995.
 - [26] U. Schubert, *The reaction $pp \rightarrow pp\eta$ Close to Threshold*, PhD thesis, Uppsala University, 1995.
 - [27] J. Dyring, *Detailed Studies of the Reaction $pp \rightarrow pp\eta$ using a Straw Chamber Tracking Device*, PhD thesis, Uppsala University, 1997.
 - [28] S. Häggström, *Production of η -mesons in Proton-Neutron collisions*, PhD thesis, Uppsala University, 1997.
 - [29] L. Gustafsson et al., *IEEE Trans. Nucl. Sci.* **41** (1994) 1155.
 - [30] *VALET-PLUS User's Guide*, CERN DD-Division OC-group.
 - [31] *FASTBUS Smart Card Controller*, Fermilab Computing Division HN96.
 - [32] J. Zabierowski, *Nucl. Inst. and Meth. A* **338** (1994) 577.

-
- [33] H. Calén, *Overview of the WASA-PROMICE Offline Programs*, Internal report TSL, Uppsala, updated continuously.
 - [34] CERN Program Library Short Writeups (1993), *Catalog of Program packages and entries*.
 - [35] CERN Program Library Long Writeup W5013(1993), *FOWL*, A general Monte Carlo phase space program.
 - [36] CERN Program Library Long Writeup W5013(1993), *GEANT*, Detector Description and Simulation tool.
 - [37] CERN Program Library Long Writeup I101(1993), *EPIO*, User's Guide.
 - [38] CERN Program Library Long Writeup Y250(1995), *HBOOK*, Reference Manual.
 - [39] CERN Program Library Long Writeup Q121(1993), *PAW*, Physics Analysis Workstation.
 - [40] V. Avdeichikov, *Nucl. Phys. A* **626** (1997) 439.
 - [41] D. Reistad, Private communication.
 - [42] V. Ziemann, Private communication.
 - [43] J. Greiff, *Investigation of Inelastic Reactions in Deuteron Proton Collisions Between $T_d = 437$ and 559 MeV Using the PROMICE/WASA Detector of CELSIUS*, PhD thesis, Uppsala University, 1999.
 - [44] H. Calén, Private communication.
 - [45] G. R. Kurz, *$\pi^+\pi^-$ -Identifikation in SzintillationsZählern*, Diploma Thesis, Tübingen University, 1995.
 - [46] W. R. Leo, *Techniques for Nuclear and Particle Physics Experiments*, Springer-Verlag, 1992.
 - [47] R. A. Cecil et al., *Nucl. Inst. and Meth.* **161** (1979) 439.
 - [48] Particle Data Group, *Particle Physics Booklet*, American Institute of Physics, 1996.

- [49] B. A. Ryan et al., *Phys. Rev.* **D 3** (1971) 1.
- [50] R. A. Arndt et al., *Phys. Rev.* **C 50** (1994) 2731.
- [51] R. A. Arndt et al., *Phys. Rev.* **C 56** (1997) 3005.
- [52] R. A. Arndt et al., *Nucl. Theory* **0004039** (2000) .
- [53] D. Alberts et al., *Phys. Rev. Lett.* **78** (1997) 1652.
- [54] *The SAID Program: A Guide for Users*, Virginia Tech Physics Department.
- [55] G. Fäldt and C. Wilkin, *Phys. Rev.* **C 56** (1997) 2067.
- [56] J. Złomańczuk, *Phys. Lett.* **B 436** (1998) 251.