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Measurement of $\pi^- p \rightarrow \pi^- p \pi^0$ and $\pi^- p \rightarrow \pi^+ \pi^- n$ near Threshold and Breaking of Chiral Symmetry

OMICRON Collaboration

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Abstract

The results from a full-kinematics measurement of $\pi^- p \rightarrow \pi^- p \pi^0$ and $\pi^- p \rightarrow \pi^+ \pi^- n$ reactions in the incident π^- momentum region from 295 to 450 MeV/c are presented with emphasis on the determination of the chiral symmetry breaking parameter ξ from the data. In the $\pi^+\pi^-$ invariant mass distribution effects of a strong $\pi^+\pi^-$ interaction are observed. A value of $\xi = -0,5 \pm 0,8$ is extracted from threshold extrapolations of the $\pi^- p \rightarrow \pi^+ \pi^- n$ amplitude. For $\pi^- p \rightarrow \pi^- p \pi^0$ we present a model-independent determination of ξ from our data closest to the threshold. The result $\xi = 0,1\ ^{+0,5}_{-0,7}$ leaves Weinberg's prediction of $\xi = 0$ the only remaining choice.

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There is considerable theoretical interest in $\pi p \rightarrow \pi\pi N$ reactions near threshold, regarding them as an information source on pion-pion scattering. Using current algebra, PCAC and chiral symmetry, Weinberg gave a prediction on π-π scattering lengths (1) and suggested the experimental study of threshold pion production as one of the best tools to study pion-pion scattering. Olsson and Turner (2) extended Weinberg's ideas to show that integrated cross-sections for $\pi p \rightarrow \pi\pi N$ reactions depend on a single parameter ξ, which determines the way chiral symmetry is broken on the level of the phenomenological Lagrangian. Weinberg's prediction of $\xi = 0$ was found to be consistent with the quark model, but other values ($\xi = 1, 2, -2$) were also proposed (3).

Despite all this demand there was little experimental information on $\pi p \rightarrow \pi\pi N$ reactions available in the threshold region (4). Some data existed for the $\pi^- p \rightarrow \pi^+\pi^- n$ channel, yet suffering either from low statistics or incomplete kinematic information, both essential to estimate effects of possible final state interactions. For $\pi^- p \rightarrow \pi^- p \pi^\circ$ only measurements at pion momenta above 390 MeV/c could be found, the threshold momentum being at 270 MeV/c.

Therefore we decided to perform a set of full-kinematics measurements of $\pi^- p \rightarrow \pi\pi N$ reactions (5) with π^- beams from the CERN SC using OMICRON, a large volume magnetic spectrometer (Fig 1). The π^- momentum range covered was from 295 to 450 MeV/c in 20 MeV/c steps. A cylindrical vessel (80 x ø15 cm^2) filled with hydrogen at 1.2 MPa was used as the target. The beam particle as well as both charged secondaries were detected in sets of MWPC's or drift chambers. Signals from scintillation counters were used for trigger formation and provided pulse-height and time-of-flight information for particle identification. Over 200 data tapes were written, a third of them at the beam momentum closest to the threshold.

In the off-line analysis hits in chambers were grouped into tracks and a common vertex of a beam and two secondary tracks was searched for. Then particle momenta at the vertex were reconstructed. Pulse-height and time-of-flight information provided a clear separation of protons versus pions and electrons in the whole momentum range of interest. On the other hand the pion versus electron separation was possible only for momenta below 100 MeV/c. The knowledge of momenta of the beam and both secondary particles together with their identity gives a complete kinematical description for a three-body reaction and allows for the reconstruction of the missing mass of the neutral particle.

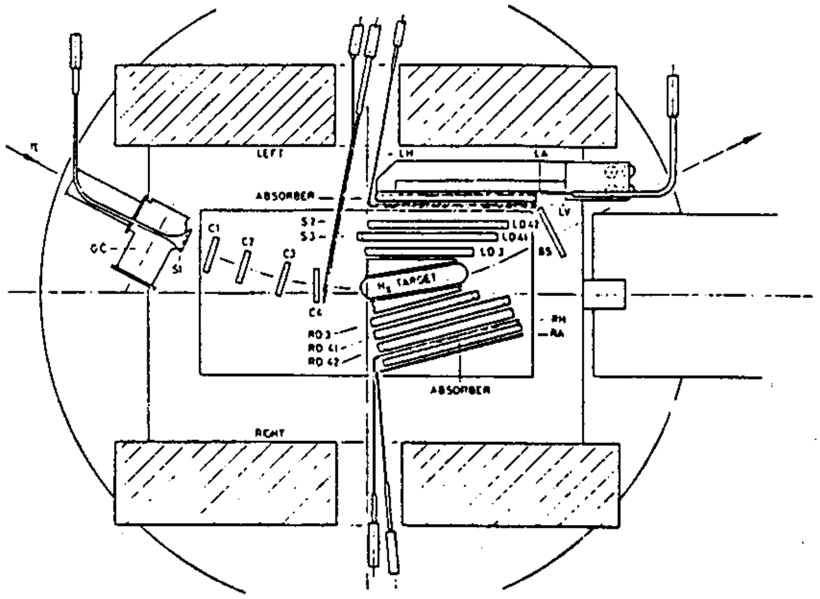


Figure 1: The experimental set-up

The geometrical acceptance and efficiency of the detection system were determined by a Monte-Carlo simulation. The evaluation of elastic scattering cross-sections (6) gave an independent normalization check of our data.

The selection of $\pi^-p \rightarrow \pi\pi N$ events was based on geometrical and kinematical properties of these reactions (7). The number of extracted events varied with beam momenta from 90 to 1600 for the $\pi^-p \rightarrow \pi^+\pi^-n$ and from 6 to 430 for the $\pi^-p \rightarrow \pi^-p\pi^\circ$ reaction channel. From these events integrated cross-sections and differential distributions were obtained.

Integrated cross-sections with statistical and systematic errors quoted separately are summarized in table 1 and a comparison with previous measurements is shown in fig. 2. A good agreement with existing data can be seen. One should note that our lowest datum point is only 11 MeV CMS kinetic energy above threshold in the $\pi^-p \rightarrow \pi^+\pi^-n$ case, this number being 17 MeV for $\pi^-p \rightarrow \pi^-p\pi^\circ$.

Table 1: Integrated cross sections for $\pi^- p \rightarrow \pi^+ \pi^- n$ and $\pi^- p \rightarrow \pi^- p \pi^0$ as a function of the incident pion momentum p_0. Δp_0 indicates the RMS beam momentum spread. Statistical and systematic errors are quoted separately.

$p_0 \pm \Delta p_0$ [MeV/c]	$\sigma(\pi^- p \rightarrow \pi^- p \pi^0)$ [μb]	$\sigma(\pi^- p \rightarrow \pi^+ \pi^- n)$ [μb]
295±9	0.75 ± 0.3 ± 0.3	5.1 ± 1.1 ± 0.5
315±10	2.2 ± 0.6 ± 0.4	20 ± 2.4 ± 1.8
334±10	8.5 ± 1.4 ± 0.8	51 ± 10 ± 6
354±10	20 ± 3 ± 4	118 ± 15 ± 13
375±11	27 ± 4 ± 4	211 ± 27 ± 24
394±10	50 ± 4 ± 12	327 ± 18 ± 37
413±11	73 ± 4 ± 14	477 ± 17 ± 53
432±11	119 ± 8 ± 18	785 ± 55 ± 88
450±12	157 ± 9 ± 36	1052 ± 42 ± 118

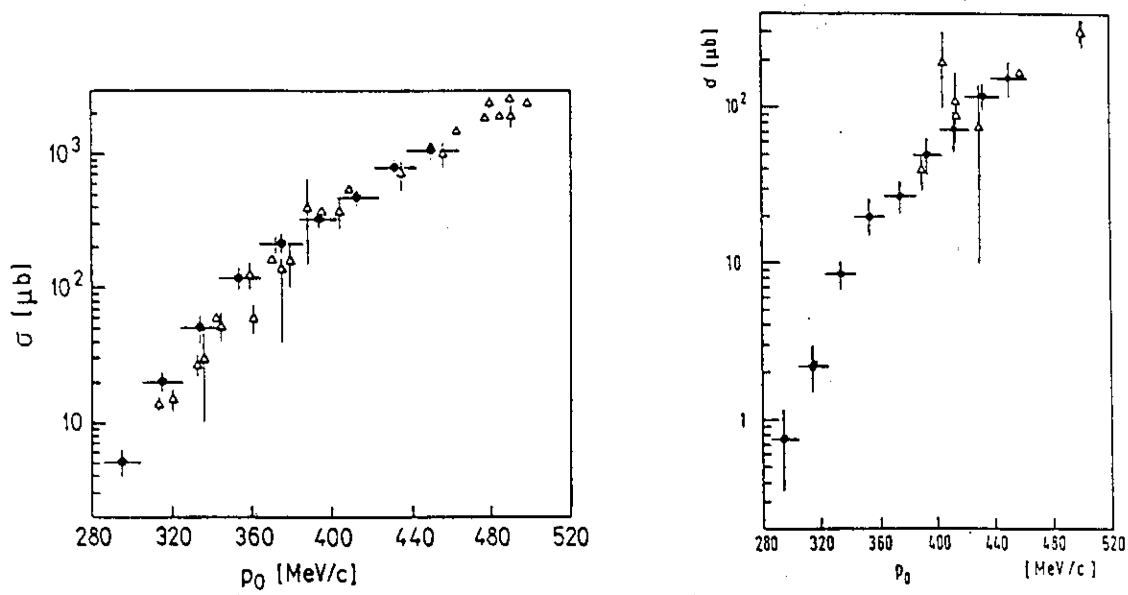
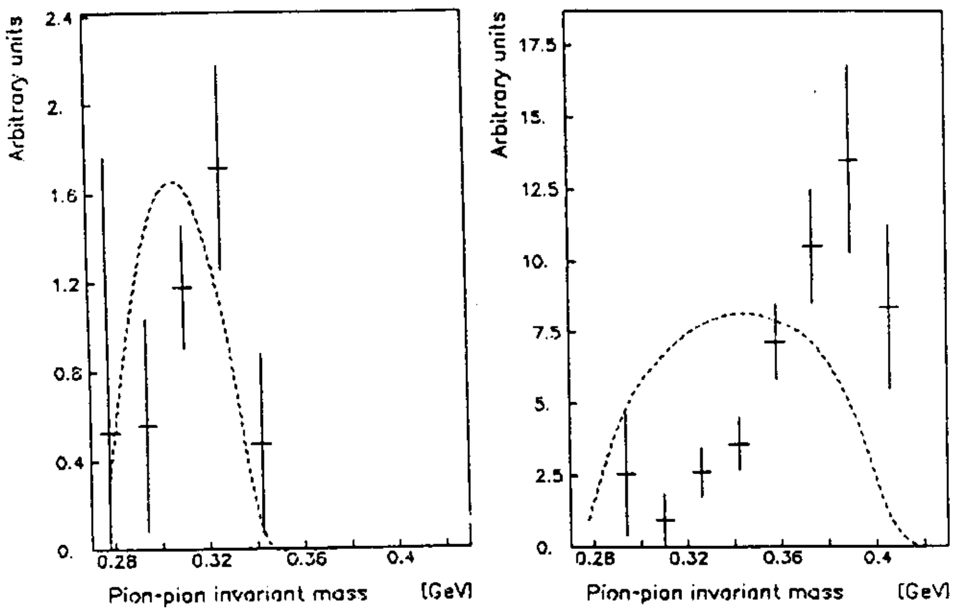


Figure 2: Integrated cross sections for $\pi^- p \rightarrow \pi^+ \pi^- n$ (left) and $\pi^- p \rightarrow \pi^- p \pi^0$ (right) as measured in this experiment (full circles) compared to previous experimental studies. Statistical and systematic errors have been summed in quadrature.

Differential distributions show different behaviour for each reaction channel. For $\pi^- p \to \pi^- p \pi^0$ no deviations from distributions according to phase space were observed. The significance of this observation is limited by poor statistics, sufficent only for one dimensional distributions, which could be disturbed by the fact, that the entire phase space was not covered by our apparatus. In $\pi^- p \to \pi^+ \pi^- n$ differential cross-sections the most striking effect can be seen in the $\pi^+\pi^-$ invariant-mass distributions, which exhibit an enhancement at high invariant masses (Fig. 3). This effect has been previously observed at higher energies. The pion pairs are found to be distributed isotropically in the $\pi^+\pi^-$ CMS, suggesting that the two pions are produced in a relative s-state. No significant evidence for Δ or ρ production could be found neither in the $\pi^\pm n$ invariant mass nor in various angular distributions. Thus our data suggest a strong $\pi^+\pi^-$ interaction, which could be attributed to a low-lying broad $J=0^+$ resonance. The isospin of this resonance should be zero since we do not see any effect in the $\pi^- p \to \pi^- p \pi^0$ channel.



P_o = 354 MeV/c P_o = 450 MeV/c

Figure 3: $\pi^+\pi^-$ invariant-mass spectra measured at 354 and 450 MeV/c. The dashed line represents the distribution according to phase space.

To compare with theoretical threshold predictions based on chiral symmetry we have to estimate the threshold value of the reduced amplitude **a** defined by

$$|a|^2 = \sigma/Q^2 \cdot PHS \qquad (I)$$

where PHS is the phase space factor in a nonrelativistic approximation given by

$$PHS = 2.56 \times 10^4 \cdot T^2/Q \quad \mu b.c/GeV^3 \qquad (II)$$

Here T is the CMS kinetic energy and Q the initial CMS momentum. The threshold value of **a** is connected to the value of the chiral symmetry breaking parameter ξ by (2)

$$|a(\pi^- p \rightarrow \pi^+\pi^- n)| = -1.21 + 0.53\,\xi \qquad (IIIa)$$
$$|a(\pi^- p \rightarrow \pi^- p\, \pi^\circ)| = 0.47 + 0.19\,\xi \qquad (IIIb)$$

In the evaluation of these formulae the pion decay constant was taken at its Goldberger-Treimann value of 87 MeV.

Because of the observed strong $\pi^+\pi^-$ final state interaction an extrapolation of the reduced amplitude to its threshold value is needed to estimate ξ from our data on the $\pi^- p \rightarrow \pi^+\pi^- n$ reaction. As the energy dependence of the amplitude is not known a priori, a wide range of functions was selected and fitted to our data. Three such examples, which

Table 2: Threshold amplitudes and χ^2's for seven degrees of freedom as obtained from the fit

Fitted function	$\|a(T=0)\|$	χ^2
$\|a\| = \|a(T=0)\| + const \times T$	1.74 ± 0.14	1.26
$\|a\|^2 = \|a(T=0)\|^2 + const \times T$	1.62 ± 0.19	0.91
$\|a\| = \|a(T=0)\| + const \times \sqrt{T}$	1.14 ± 0.24	0.84

all yield acceptable χ^2 values, are shown in table 2. The difference of threshold values obtained from fits to different functions was taken as the measure of the systematic error of the fit. One can see, that this error clearly dominates the uncertanity in the determination of **a** and then ξ from our data.

The final result from our data on the $\pi^- p \rightarrow \pi^+\pi^- n$ reaction is $|\mathbf{a}| = 1.5 \pm 0.4$, from which, in principle, two values for ξ follow: $\xi_1 = -0.5 \pm 0.8$ and $\xi_2 = 5.1 \pm 0.8$.

The cross-section for $\pi^- p \rightarrow \pi^- p \pi^\circ$ close to threshold can be decomposed as the sum of the symmetric and antisymmetric part, σ^+ and σ^-. The symmetric part corresponds to s-wave pions with $I_{\pi\pi}=2$, while the antisymmetric part represents the two-pion p-wave ($I_{\pi\pi}=1$). One can form two reduced amplitudes

$$|\mathbf{a}_+| = \sigma^+/(Q^2 \cdot PHS) \qquad \text{(IVa)}$$

$$|\mathbf{a}_-| = \sigma^-/(\overline{(\mathbf{q}_1 - \mathbf{q}_2)^2} \cdot PHS) \qquad \text{(IVb)}$$

Here $\mathbf{q}_1$ and $\mathbf{q}_2$ are the CMS vector momenta of secondary pions. In the threshold limit $\mathbf{a}_+$ corresponds to **a** in (IIIb), while $\mathbf{a}_-$ is ξ-independent with a value of 0.92 (8).

To see where the threshold approximation is still adequate to describe pion production we take note of the fact, pointed out by Dashen and Weinstein (9), that $\pi p \rightarrow \pi\pi N$ amplitudes derived from the phenomenological Lagrangian are valid only through terms linear in pion momenta. The evaluation of higher order terms is considered to be highly model-dependent. Arndt et al. (8) calculated $\pi p \rightarrow \pi\pi N$ amplitudes by evaluating graphs derived from the phenomenological Lagrangian up to the tree level. The comparison of their results on the cross-section with the threshold approximation, obtained by summing σ^+ and σ^+, shows, that up to 320 MeV/c the results coincide. So we considered our first two data points at 295 and 315 MeV/c as being suitable for the evaluation of ξ in a model-independent way.

From these two data points we extract for the symmetric reduced amplitude $\mathbf{a}_+$

$$|a_+| = 0.54 ^{+\,0.17}_{-\,0.26} \qquad (295\ \mathrm{MeV/c})$$

$$|a_+| = 0.45 ^{+\,0.12}_{-\,0.15} \qquad (315\ \mathrm{MeV/c})$$

The combined average used in equation (IIIb) yields again two values for the symmetry breaking parameter ξ: $\xi_1 = 0.1 ^{+\,0.5}_{-\,0.7}$ and $\xi_2 = -5.0 ^{+\,0.5}_{-\,0.7}$

Combining the two measurements allows us to resolve the sign ambiguity in the amplitude and reject ξ_2 in both evaluations. For our final result on ξ we quote the value obtained by the model-independent analysis of the $\pi^-p \rightarrow \pi^-p\pi^\circ$ reaction

$$\xi = 0.1 ^{+\,0.5}_{-\,0.7}$$

noting that our result from the threshold approximation of the $\pi^-p \rightarrow \pi^+\pi^-n$ reduced amplitude is in a good agreement with this value.

To conclude we have performed a full-kinematics measurement of $\pi^-p \rightarrow \pi^-p\pi^\circ$ and $\pi^-p \rightarrow \pi^+\pi^-n$ reactions in the incident π^- momentum region from 295 to 450 MeV/c. In $\pi^+\pi^-$ invariant mass distributions we see effects of a strong $\pi^+\pi^-$ final state interaction. From the threshold extrapolation of the $\pi^-p \rightarrow \pi^+\pi^-n$ reduced amplitude we deduce the value of $\xi = -0.5 \pm 0.8$, the error being dominated by the systematics in the extrapolation procedure. For the $\pi^-p \rightarrow \pi^-p\pi^\circ$ reaction we estimate, that two of our data points closest to the threshold are suitable for the determination of ξ in a model-independent way. From this analysis we qoute our final result as $\xi = 0.1 ^{+\,0.5}_{-\,0.7}$. The results of these measurements suggest Weinberg's prediction of $\xi = 0$ as the only acceptable choice.

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