Pionic Charge Exchange on the Proton from 40 to 250 MeV

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Abstract

The total cross sections for pionic charge exchange on hydrogen were measured using a transmission technique on thin CH₂ and C targets. Data were taken for π⁻ lab energies from 39 to 247 MeV with total errors of typically 2 % over the Δ-resonance and up to 10 % at the lowest energies. Deviations from the predictions of the SAID phase shift analysis in the 60-80 MeV region are interpreted as evidence for isospin-symmetry breaking in the s-wave amplitudes. The charge dependence of the Δ-resonance properties appears to be smaller than previously reported.

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The study of pion-nucleon interactions is a testing ground for the understanding of hadronic forces in terms of chiral perturbation theory of the QCD. Over the past decade this has motivated several experiments on $\pi^+p$ and $\pi^-p$ elastic scattering off unpolarized and polarized hydrogen targets with the aim to determine, via a phase-shift analysis (PSA), the $\pi N \sigma$-term and the $\pi NN$ coupling constant. A third quantity of interest is the extent to which isospin symmetry is broken in the strong interaction. In chiral perturbation theory this is expected to arise from the difference between up- and down-quark masses and from electromagnetic effects on the quark level. Here, we study only effects beyond hadronic mass differences and Coulomb interaction.

We exploit the so-called triangle identity which, assuming isospin conservation, relates the amplitudes for pionic charge exchange (CX) $\pi^-p \rightarrow \pi^0n$ to those for elastic $\pi^+p$ and $\pi^-p$ scattering. This method was used before by who independently reported isospin-symmetry breaking amounting to about 7% in the $s$-waves amplitudes near 50 MeV pion energy. In detail, however, their amplitudes differ substantially from each other and therefore their seeming agreement may be fortuitous. The reason for this uncertainty may be found in the data basis which was particularly scarce for the CX reaction. This motivated our present measurement of the CX cross sections. Unlike refs. we did not employ $\pi N$ interaction models in our analysis but rather used reaction amplitudes as provided by the SAID-PSA which achieves good fits to the high-quality elastic scattering data that are now available (see e.g. ). Such fits mean that the elastic scattering amplitudes are under control. Hence, if isospin is conserved, this should allow also reliable predictions of the CX cross sections. Significant deviations from such predictions, therefore, are considered as indications of isospin-symmetry breaking.

With the aim of measuring the total CX cross sections over a large energy range, notably at energies below the $\Delta$-resonance, we performed transmission experiments where the loss of negative pions on a hydrogen target was recorded. As in a previous experiment we used solid CH$_2$ targets to avoid the complications, occurring notably at low pion energies, associated with a liquid hydrogen target, such as the presence of windows, the control and stability of the target volume and the impossibility of a $4\pi$-detector geometry. (It is remarkable that the pioneering experiment by Bugg et al. used a liquid hydrogen target, however only for energies above 90 MeV). The carbon background was subtracted in background runs on graphite targets. An essential improvement in the present work was
the data acquisition system which recorded the signals of all detectors for every incoming negative pion and thus allowed an off-line analysis on an event-by-event basis.

The experiments were performed at the pion beam lines $\pi M1$ and $\pi E3$ of the PSI meson factory at Villigen, Switzerland, for high and low pion energies, respectively. The energy calibration of the $\pi M1$ beam line as reported in [12] was checked and confirmed by time-of-flight measurements using protons of the same momentum as the pions. The calibration of the $\pi E3$ beam line was adopted from [13]. For both beam lines the reported [12, 13] calibration errors amount to 0.3 % of the pion momentum.

A trigger signal for the data acquisition system was produced when particles traversing the three beam defining scintillation detectors S1, S2 and S3 (see fig. 1) had the correct timing, relative to the cyclotron RF signal (50.63 MHz), and had the energy deposition expected for pions. The detector for outgoing charged particles was a carefully designed nearly full $4\pi$ scintillator box $20 \cdot 10 \cdot 10 \text{ cm}^3$ in size, consisting of six scintillator plates, 2 mm thick with the exception of the “back” detector which was 7 mm thick, needed to achieve very high efficiency. The only opening in this box was the beam entrance hole in the “front” detector, $3 \cdot 3 \text{ cm}^2$ in size which encompassed the beam definition counter S3. All six detectors forming the box were read out on two ends via lucite light guides. Each detector was followed by an efficiency counter, 3 mm thick. Only for the “back” detector which was hit by the full pion beam did we use three efficiency counters, while the “front” detector had none for geometrical reasons. Following a trigger signal all charge-to-digital converters (QDCs) integrating over a period of 50 ns and all time-to-digital converters (TDCs) gated for 150 ns were read out.

The target was mounted in a slide attached to the “down” detector about 6 cm downstream of the “front” detector. Target changes were performed automatically by a robot which moved the “down” detector and exchanged the targets in the desired order whenever a preset number of events was reached which was typically about every 20 to 30 minutes. Three pairs of $\text{CH}_2$ and C targets 40 mm high and 35 mm wide with areal densities ranging from about 300 to 800 mg/cm$^2$ were used. These were the same targets as in [10] but the weights and chemical composition were carefully checked and validated consistently at three independent laboratories. The pairs of targets were manufactured so that traversing pions deposited the same amount of energy in the corresponding $\text{CH}_2$ and C targets.

The transmission $T$, defined as the ratio of the number of events with a signal in the box
FIG. 1: Lay-out of the experimental set-up. The pion beam enters from the left.

detector to the number of triggers, was measured for both targets of a thickness-matched pair and was corrected for the “zero” transmission $T_0$ obtained without a target. Typical values were $T_i = 99.5\%$ and $T_0 = 99.9\%$. The resulting cross sections $\sigma_i$ were derived from the expression $T_i = T_0 e^{-\alpha_i \sigma_i}$ with $i=C, CH_2$ and $\alpha_i$ representing the target thicknesses. In practice the number of counts was first corrected for detector efficiencies with typical values in excess of 99\% (99.998\% for the “back” detector) and for the fraction of random events. The latter was determined from an analysis of the TDC spectra. The corrections for randoms, being of the order of 2 to 10\%, were larger than naively expected from the trigger rates of about 10 kHz since the particles from the extended beam which missed the beam defining detectors created single rates of up to 1 MHz in the front and back detectors.

Using GEANT3 [14] and GEANT4 [15] Monte Carlo simulations with a detailed representation of all detector components [16, 17], the resulting raw CX cross sections $\sigma_{CX} = (\sigma_{CH_2} - \sigma_C)/2$ were corrected for the (false) detection of gammas (6 to 8\%) and of neutrons (1 to 4\%) and for Dalitz decays (1.2\%). Corrections were also made for the decay of pions very close to the target where the time-of-flight discrimination was ineffective. Moreover, the known cross sections for radiative pion capture ($\approx 0.7$ mb) had to be subtracted. No corrections were necessary for the charged back-scattered pions escaping through the beam entrance hole since the corresponding recoil protons were detected in the “back” detector. For details of the experiment and the analysis see [17].

Various tests were performed in the course of the experiments. Trigger rates differing by a factor of three yielded results agreeing within the statistical errors. Runs with the
trigger set to electrons and muons, respectively, of the same momentum as pions, gave the expected result of zero within the statistical errors. Most informative were test runs with positively charged pions performed for energies below 130 MeV. While these also gave zero cross sections for lab energies above 100 MeV, slightly negative cross sections emerged at the lowest energies, with a maximum deviation of a few tenths of a mb at 40 MeV, depending on the target thickness. This was interpreted as due to absorption effects in the targets and checked by the use of target pairs with different thicknesses. These absorption effects could not be simulated because of the lack of detailed knowledge of the reaction products. Consequently, the results below 100 MeV were corrected for absorption effects by subtracting from the CX cross sections the apparent cross sections from the π⁺ tests at the same energies and target thicknesses and assigning conservatively a systematic error of 100 % of this correction. This error dominates the total error at low energies and limits the energy range accessible to our technique to about 40 MeV.

Other systematic errors were estimated to be (i) 30 % of the corrections applied to account for random events, (ii) about 1 % of the CX cross section for Monte-Carlo uncertainties, and (iii) uncertainties of similar size arising from the detector thresholds which were carefully determined by replaying the analysis with various thresholds. Statistical errors amounted to 1 to 2 % throughout. All errors were added in quadrature. We emphasize that there are no additional normalisation errors. The results are presented in table I.

The cross sections and total errors of the experiments are shown in fig. 2 separately for the two pion beam lines used. Also shown are the predictions of the phase-shift analyses KH80 [18] and SAID-FA02 [9]. The former are significantly too high on the low-energy slope of the Δ-resonance, not too surprisingly in view of the limited πN data base available at that time; the latter show an excellent agreement with our data with the exception of the energy region from 60 to 80 MeV. In that region the data were corroborated by measurements in both beam lines with very different beam properties and rates.

For clarity fig. 2 shows only results from transmission experiments since these generally have smaller errors than integrated differential cross sections. In the resonance region the present data are able to resolve the discrepancy between [11] and [10] which partly motivated this experiment. We confirm the results of [11], with the possible exception of their 90.9 MeV data point which is slightly high. On the other hand, the data from [10] are systematically low by about 3 % which is now traced to originate from too small Monte-Carlo corrections.
TABLE I: Experimental total charge-exchange cross sections. The errors are combined statistical and systematic errors including normalisation uncertainties.

| $E_{lab}$ [MeV] | $\sigma_{CX}$ [mb] |
|-----------------|-------------------|
| 38.9            | 5.6(5)            |
| 43.0            | 6.3(8)            |
| 47.1            | 6.4(7)            |
| 55.6            | 7.3(6)            |
| 64.3            | 7.8(5)            |
| 65.9            | 8.3(5)            |
| 75.1            | 9.4(4)            |
| 76.1            | 10.3(6)           |
| 96.5            | 16.3(4)           |
| 106.9           | 20.0(5)           |
| 116.6           | 25.3(3)           |
| 126.7           | 29.5(6)           |
| 136.8           | 36.4(5)           |
| 164.9           | 48.1(5)           |
| 176.9           | 48.0(5)           |
| 197.0           | 43.3(4)           |
| 217.0           | 36.5(4)           |
| 247.0           | 26.5(3)           |

At low energies, data of comparable quality were taken by [19] and [20] using a $\gamma$ ray detector to observe the $\pi^0$ decays. The results generally agree within errors with the present work.

Turning to comparisons between our experimental results and predictions, the total cross sections calculated with the SAID-FA02 phase shifts yield $\chi^2=32.6$ for the 18 data points. There are some systematic deviations between the data and those predictions in the energy range of 60-80 MeV which we tentatively interpret as evidence for isospin-symmetry breaking. Prompted by the findings of [7, 8], we first attempted to improve the fit by modifying the $s$-wave part of the SAID CX cross section. To this end we multiplied the (hadronic) $s$-wave amplitudes $|S_{31} - S_{11}|$ (with the notation $L_{2I,2J}$) by an energy-independent factor $f$, thereby keeping the small Coulomb corrections ($\approx 4\%$ in $\sigma$) as in SAID. The best fit (dotted line in the expanded presentation of fig. 3) was obtained with a modification of the SAID $s$-wave amplitudes by $f - 1 = (-4.4 \pm 1.5)\%$ which yielded an improved $\chi^2 = 22.4$. Comparisons with the data show (fig. 3) that this modification is unfavourable at higher energies. Not surprisingly, therefore, the fit yields a larger reduction of $(-8.1 \pm 2.2)\%$ if we...
FIG. 2: Total CX cross sections from this and preceding [10, 11] transmission experiments. The error bars represent the total errors. Results from both pion beam lines used in the present experiment are shown separately. The solid and dashed curves represent the results from the phase shift analyses SAID-FA02 [9] and KH80 [18], respectively.

fit only data points below 107 MeV. In order to express the result in terms of (real) phases we rewrite \( |S_{31} - S_{11}| = |\sin(\delta_{31} - \delta_{11})| \) i.e. in a way which underlines that CX cross sections are sensitive only to the isospin-odd phase difference. Recent elastic scattering data [2] fix this phase difference e.g. at 45 MeV to about 11°. The (4.4 ± 1.5) % reduction of the s-wave amplitude suggested by the fit amounts to a reduction of the phase difference \( |\delta_{31} - \delta_{11}| \) by (0.5 ± 0.16)° which is a significant change given the precision of recent experiments (see e.g. [2]).

As the observed deviations from the SAID predictions occur in a region where the s-wave and the p-wave contributions to the CX-cross section are about equal, it was important to check if modifications in the p-wave amplitudes, notably in the dominant \( P_{33} \)-amplitude, would also lead to improved fits to the data in general and in this region in particular. Of course, the charge dependence of the \( \Delta \)-resonances implied by this procedure would
FIG. 3: Cross sections from this experiment with total errors, plotted as percent deviation from the SAID-FA02 [9] predictions. The curves represent the results of fit procedures with a slight modification of the S-amplitudes (dotted), the $P_{33}$-amplitude (dashed) or both (solid).

also constitute an effect of isospin-symmetry breaking. Again we kept the small Coulomb corrections as in SAID by replacing only the relevant hadronic amplitudes in the expression for the total CX cross section. We first observed that the $P_{33}$ part of the SAID cross sections agrees, in the resonance region, to better than 1 % with a relativistic Breit-Wigner (BW) resonance shape normalized to exhaust the unitarity limit [12], if one chooses resonance energy and width as $\bar{W} = 1231.2 \pm 0.4$ MeV and $\bar{\Gamma} = 112.4 \pm 1.0$ MeV, respectively. (These values stand for a $\Delta$-resonance that is a charge average of the $\Delta^{++}$- and the $\Delta^{0}$-resonances, averaged in a somewhat ill-defined way since it depends on the relative weights of various $\pi^+p$ and $\pi^-p$ data sets in the SAID input.)

We then applied two different approximations in replacing the $P_{33}$ partial wave amplitude by a BW-based form, varying the BW parameters by a least-squares method. Improvements
in the fits were indeed achieved by minor changes in the resonance parameters. Both our approaches yielded nearly identical best-fit values. Therefore we quote their averages and add in quadrature to the statistical error half of their difference as a systematic error.

(i) Varying only the resonance parameters (keeping the s-wave amplitudes as in SAID) we obtain $\chi^2=20.6$ (dashed line in fig. 3) with $W^0 = 1231.1 \pm 0.6$ MeV, and $\Gamma^0 = 110.9 \pm 1.2$ MeV. (ii) Varying both the resonance parameters and the scale factor $f$ on the s-wave amplitudes we obtain $\chi^2=19.1$ for the 18 data points (solid line in fig. 3), with $W^0 = 1231.3 \pm 0.6$ MeV, $\Gamma^0 = 112.5 \pm 1.9$ MeV and with the s-wave amplitudes reduced by $(3.2\pm2.9)$ % relative to the SAID values. Note that, on the basis of the $\chi^2$ per degree of freedom, none of the three fits displayed in fig. 3 is preferable while all of them are superior to the SAID FA02 solution.

Whereas the results for $W^0$ are perfectly stable one observes a clear correlation between the s-wave scaling and the derived resonance width $\Gamma^0$: obviously the slight depression of the CX cross section between 60 and 80 MeV may be reproduced by a reduced resonance width or by reduced s-wave amplitudes. But in both cases our result for the width of the $\Delta^0$-resonance is substantially smaller than e.g. the $\Gamma^0 = 117.9\pm0.9$ MeV reported by [12, 21]. Considering the accuracy of the present data in the resonance region we consider this a significant result. For the $\Delta^{++}$ typical resonance parameters are listed [21] as $W^{++} \approx 1231$ MeV and $\Gamma^{++} \approx 111$ MeV. We therefore conclude that within about 1 MeV there is no difference between the Breit-Wigner parameters of the $\Delta^{++}$ and the $\Delta^0$. Interestingly, recent reanalyses [9, 22] of the previously available data already yielded smaller differences between the masses and widths, respectively, of the $\Delta^{++}$ and the $\Delta^0$ than had been reported by [12].

In conclusion, we have measured by a transmission technique the $\pi^-p$ CX total cross sections over the $\Delta$-resonance and below, covering a larger energy range than previous experiments. The accuracy of about 2 % in the resonance region made it possible to resolve the existing discrepancy between two previous transmission experiments and to determine Breit-Wigner parameters of the $\Delta^0$-resonance. These are much closer to the values listed [21] for the $\Delta^{++}$-resonance than previously reported, indicating a weaker charge dependence in the $\Delta$ parameters. Similarly, we find indications for isospin-symmetry breaking in the s-wave amplitudes, but again they tend to be smaller than reported previously [2, 8]. Interestingly, recent calculations [23] in heavy-baryon chiral perturbation theory also predict isospin breaking effects that are quite small, e.g. $-0.7$ % in the s-waves. Finally we observe
a correlation between the deduced amount of isospin-symmetry breaking in the $s$-waves and
the Breit-Wigner parameters of the $\Delta$-resonances that should be kept in mind in future
attempts to determine isospin violations. Needless to say, the present simple analysis based
on the SAID program should be replaced eventually by a full phase shift analysis with a
data base including the present cross sections.

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