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Integral cross sections for $\pi^- p$ interaction in the 3,3 resonance region

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Total cross sections for the $\pi^- p$ single charge exchange and 20° "partial– total" cross sections have been measured between 126 and 202 MeV pion energy. The former are about 4% below similar results of Bugg et al. and (5–10)% below predictions made with currently accepted phase shifts. The latter agree quite well with calculations.

New measurements of pion–proton differential cross sections at low energies and over the 3,3 resonance region have been performed in recent years with the aim of improving the consistency of the data [1–4]. As some discrepancies between different data sets seem to be due to normalization of the cross sections, additional measurements of integral cross sections could help in sorting out those inconsistencies. Such measurements for π^+ have been performed recently [5–7] and showed very good agreement with predictions made with several of the currently accepted sets of phase shifts. It is therefore of interest to perform similar measurements with π^- where the sensitivity of the cross sections to the various partial waves is different from that for the π^+. Such measurements are also important in connection with dispersion relation analysis relating data at low energies to data over the resonance [8,9].

The present letter reports on measurements of integral cross sections for $\pi^- p$ interactions between 126 and 202 MeV. We have measured the total cross section for the $\pi^- p \to \pi^0 n$ single charge exchange (SCX) reaction and also the "partial–total" cross section for 20° (lab.) [6] which is closely related to the conventional total cross section. This work completes a set of integral cross section measurements performed recently with a common experimental setup [5–7].

The total cross section for the SCX was measured by the method of Bugg et al. [10]. A major difference between the present experiment and that of Bugg et

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al. was that we chose to use solid targets of polyethylene and graphite to obtain the cross section for hydrogen by subtraction of the carbon contribution, whereas Bugg et al. used a liquid hydrogen target. The solid targets were preferred because of their precisely known thickness, the better-defined geometry, and because with solid targets one can use a tightly closed anti-coincidence detector (see below). The thickness of the targets was in the range of 0.4– 0.85 g/cm^2 and pairs of targets were used whose thicknesses were adjusted to cause the same energy losses for pions. We used the same carefully made targets as in our previous measurements [5–7]. The target was surrounded on five sides by a box made from plastic scintillators. The experiment consists of measuring the relative number of pions incident on the target without producing an outgoing detected particle, as obtained by measuring anti-coincidences between the beam and this box detector. The box was 9×9 cm^2 in cross section and 21 cm long, with the target placed 7 cm from its upstream end so that pions elastically scattered by protons into the open back side of the box were detected by counting the accompanying protons recoiling into the forward counter. The four side counters were 3 mm thick, but the front counter was 12 mm thick to ensure very high efficiency for detecting beam pions. The efficiencies of the side counters were measured off-line and were larger than 0.999. The efficiency of the forward counter (typically 0.9998) was measured continuously with the help of a smaller efficiency counter.

As in our previous experiments, the beam was defined by a coincidence between three beam-defining counters, but this time an additional halo counter in anti-coincidence was placed 170 cm upstream of the target, to reduce chance coincidences with out-of-beam pions that may hit the box detectors. The fraction of muons and electrons in the beam was monitored by time-of-flight measurements between one of the beam-defining counters and the primary beam. The muons could clearly be separated only at energies of 161 MeV and below. However, since their fraction at that energy was 0.5%, the correction at higher energies could be made with a negligible contribution to the final error. The performance of the various coincidence units was monitored continuously by a "complementarity test", comparing the sum of coincidence and anti-coincidence events with the corresponding number of beam events. When one aims at an accuracy of 1% for a cross section measured with a transmission technique, that test has to be fulfilled to an accuracy of 10^{-5} and that was achieved in the present experiment.

In some respects the present measurements are simpler than our previous measurements of π^+p integral cross sections at lower energies [6] because the differences between the cross sections for CH_2 and C are relatively larger here. For example, at 174.5 MeV the cross sections for producing neutral particles are 228.7 ± 0.7 mb for polyethylene and 148.5 ± 0.6 mb for carbon. The reason for the relatively large differences is the small value of the effective number of nucleons in nuclei at resonance energies (2–3 for carbon) due to the strong shielding within the nucleus, which makes the contribution of the two free protons in CH_2 relatively larger. The detection of delta rays may cause systematic errors and that was minimized in the front counter by the use of two detectors in coincidence together with discrimination levels just below the pion signal. Single counters were used for the sides of the box but the intensity of energetic delta rays at larger angles is considerably smaller than at forward angles. Energy losses in the target help reduce this effect. The importance of these as well as other multiple processes can be assessed by varying the thickness of the targets. We have observed a small dependence of the measured cross sections for carbon on the thickness of the target but that dependence was not observed on the deduced cross sections for hydrogen, thus suggesting that some cancellation of multiple processes takes place in the subtraction.

The measurements were carried out by repeating 8–16 times short measurements at each energy, to reduce the chance of drifts and to check the distribution of individual results around the mean, in comparison to expectations. Beam rates were 12–25 kHz and with the 100% duty factor of the TRIUMF cyclotron there was no problem with accidental coincidences. Note that some uncertainties cancel out in the subtraction. A particularly critical test of the overall performance of the system is provided by measuring the cross section for the production of neutral particles by π^+p, which should be zero below the threshold for pion production. We have therefore measured the π^+p cross section with the box detector configuration at 125.9 and 161.1 MeV, and typical results were -0.25 ± 0.20 mb. We note that this is also a sensitive test of the polyethylene-graphite subtraction technique and this result is indicative of systematic errors.

Measurements of the "partial–total" cross sections for $\pi^- p$ were performed with the same setup used before for similar measurements for $\pi^+ p$ [5–7]. These are the cross sections for beam attenuation as measured with a detector subtending a given angle (20° in the present case) at the target. Whereas for $\pi^+ p$ this cross section is the integrated cross section for elastic scattering beyond that angle, in the case of π^- it is that integral plus the total SCX cross section. The "partial–total" cross section is an observable that can be compared with calculations, without explicitly involving the Coulomb corrections that are inevitable in the case of total cross sections [11].

Both types of measurements were performed on the M11 pion channel at TRIUMF. Independent checks on the energy calibration of the channel were made by transporting light ions through it and measuring their energy with the help of a Si detector. Several corrections must be made to the experimental results before obtaining the desired $\pi^- p$ cross sections. The largest correction is that due to the detection of neutral particles, that can take place via the detection of neutrons and gammas directly in the various detectors or indirectly following interactions in the target or in structural material. These corrections had been calculated with the help of a Monte Carlo technique and were found to be of the order of 5%. The calculations were based on the angular distributions for the SCX reaction as given by the SAID phase shifts [12], to produce the distribution in the laboratory of neutrons and gammas. For example, at 174.5 MeV and for a CH_2 target 0.711g/cm^2 thick, the overall efficiency for detecting neutrons is 2.2% and that for detecting gammas is 3.8%. For a thinner target of 0.434g/cm^2 the values are 1.7% and 2.4% respectively. A correction of 1.2% due to the $\pi^0 \to \gamma, e^+ e^-$ decay was also made. Repeating such calculations with different assumptions regarding discrimination levels suggest that the uncertainties in these efficiencies for detecting neutral particles are around 0.3%. Therefore, the contribution of errors of these corrections to the final errors are estimated to be less than 1%. Finally, the cross section for capture in flight must be subtracted from the cross section for producing neutral particles in order to obtain the proper $\pi^- p$ cross sections (SCX and "partial–total"). This was done with the help of detailed balance and the total cross section for the $\gamma n \to \pi^- p$ reaction [12].

Table 1 shows the experimental cross sections and several deduced quantities. The errors include statistical counting errors and the effect of an uncertainty of 0.5 MeV in beam energy. Small corrections due to muons from pion decays near the target have also been included. The cross sections for neutrals production are obtained directly with the box counter configuration whereas the cross sections for SCX are obtained by subtracting the cross sections for $\pi^- p$ capture. The same capture cross sections are also subtracted from the experimental "partial–total" cross sections, to produce the values in the table. Subtracting from the "partial–total" cross section the corresponding cross sections for SCX leads to the last column which is for the elastic scattering integrated beyond 20°.

Fig. 1 shows comparisons between the present re-

Table 1
Experimental results and deduced quantities.

π^- kinetic energy (lab.) (MeV)	Total σ for neutrals production (mb)	$\pi^- p$ capture σ (mb) [a]	Total σ SCX (mb)	Partial–total σ, 20° lab. (mb)	Partial-elastic σ, 20° lab. (mb)
125.9	29.7 ± 0.7	0.79	28.9 ± 0.8	42.0 ± 0.9	13.1 ± 1.0
147.8	40.8 ± 0.8	0.82	40.0 ± 0.9	60.0 ± 1.2	20.0 ± 1.3
161.1	46.0 ± 0.8	0.80	45.2 ± 0.9	65.4 ± 1.2	20.2 ± 1.3
174.5	47.1 ± 0.7	0.73	46.4 ± 0.8	69.3 ± 1.2	22.9 ± 1.3
188.1	45.1 ± 0.7	0.64	44.5 ± 0.8	66.2 ± 1.5	21.7 ± 1.6
201.7	40.3 ± 0.7	0.56	39.7 ± 0.8	59.5 ± 1.4	19.8 ± 1.6

[a] From SAID SP89 using detailed balance.

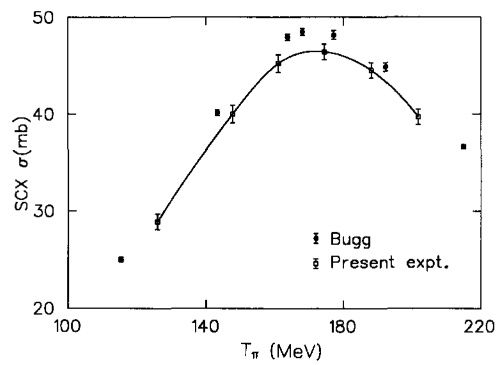

Fig. 1. Comparisons between the present experimental results for the SCX reaction and those of Bugg et al. The smooth line through the present results has been added to guide the eye.

sults for the total SCX reaction with the corresponding values of Bugg et al. [10]. A very good agreement is observed for the shape of the curves but the present results are uniformly lower by (3–4)%. Fig. 2 shows comparisons between the present results and various calculations of the SCX and the 20° "partial–total" cross sections [12,13]. It is evident that the present result are lower than the calculated values by (5–10)% presumably because the latter are based to a large degree on the experimental results of Bugg et al. It is interesting to note, however, that the agreement between the present experimental results and calculations for the "partial–total" cross sections is quite good, suggesting that whilst the balance between the SCX and the elastic scattering is somewhat different from that predicted by the phase shifts, the total cross section is predicted more correctly.

The present results for the SCX reaction are consistently below the phase shift analysis and the previous data of Bugg et al. by about 5% with our maximum cross section equal to 46.4 mb. While a 5% change may not seem large, it is important to realize that most of the difference must come from the partial waves other than the P_{33}. At resonance the P_{33}

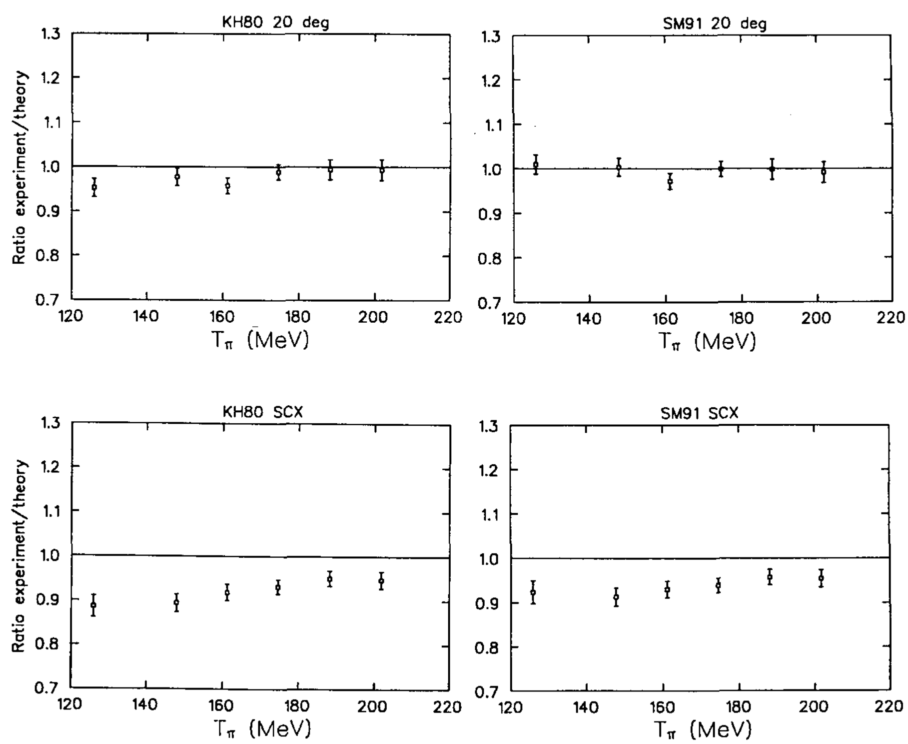

Fig. 2. Comparisons between the present experimental results and predictions made with the KH80 [13] and SM91 [12] sets of phase shifts. The lower half refers to the SCX cross section. The top half refers to the measured "partial–total" cross sections in comparison to the sum of SCX and the integrated elastic scattering.

phase shift is 90° (by definition). This allows one to calculate the contribution of the P_{33} partial wave to the total SCX cross section at resonance and it is approximately 42 mb. Since the P_{33} contribution at resonance is fixed (apart from uncertainties in the exact location of the resonance) the differences must be due to the other partial waves. Thus the meaning of the present results for the SCX reaction is that the contributions from the non-P_{33} partial waves to this reaction are reduced by about 30%.

To summarize, we have measured the total cross section for $\pi^- p$ charge exchange reaction and the "partial-total" cross section for 20° in the energy range of 126–202 MeV, to supplement integral cross sections for $\pi^+ p$ measured recently. The present results for the SCX are (5–10)% smaller than predictions made with currently accepted phase shifts. The "partial-total" cross sections agree well with calculations. It will be interesting to see if a revision of the non-P_{33} phase shifts will reduce the current discrepancies between calculated and measured differential cross sections.

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