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Charge-Symmetry Nonconservation in π^+ and π^- Elastic Scattering on ^3H and ^3He

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Abstract

Extensive new data on the superratio R are reported for π^+ and π^- elastic scattering on ^3H and ^3He at T_π=142, 180, and 220 MeV at θ_π(lab) from 40° to 110°; $R \equiv d\sigma(\pi^{+3}H)d\sigma(\pi^{-3}H)/d\sigma(\pi^{-3}He)d\sigma(\pi^{+3}He)$. In all cases R > 1, which can't be explained by electromagnetic effect and therefore indicates nonconservation of nuclear charge symmetry. The charge-symmetric ratios r_1' and r_2' also have been obtained; $r_1' \equiv d\sigma(\pi^{+3}H)d\sigma(\pi^- d)/d\sigma(\pi^{-3}He)d\sigma(\pi^+ d)$ and $r_2' \equiv d\sigma(\pi^{-3}H)d\sigma(\pi^+ d)/d\sigma(\pi^{+3}He)d\sigma(\pi^- d)$. It is found that r_1'=1 and $r_2' > 1$ in all cases.

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An intrinsic nonconservation of charge symmetry (CS) is implied by QCD[1-3] as a consequence of a 3-5 MeV difference in the masses (Δm) of the up and down quarks. This effect has approximately the same magnitude as the well established "uninteresting" violation of CS due to the electromagnetic interaction, making its unambiguous experimental determination difficult. The observed decay rate[4] for $\eta' \rightarrow \eta\pi^0\pi^0$ is consistent with the QCD predictions. Tests of CS can be classified according to their sensitivity s to the mass difference Δm. Experimental investigations include those for which (a) s=0, such as in $\vec{n}\vec{p} \rightarrow np$,[5] where the effect have been found to be small; (b) $s \propto \Delta m$, such as in the comparison of the $\pi^{+3}H$ and $\pi^{-3}He$ systems; (c) $s \propto 2\Delta m$, such as in the comparison of the π^+d and π^-d systems[6]; and (d) $s \propto 3\Delta m$, such as in the comparison of the $\pi^{-3}H$ and $\pi^{+3}He$ systems.

The present experiment investigates CS violation in elastic pion scattering on the isospin doublet ^3H and ^3He. These nuclei are the simplest many-body systems for which accurate theoretical calculations can be done. In addition, Coulomb corrections are small and the Δ resonance plays a major role in pion scattering on these very light nuclei. The importance of using trinucleon systems to understand basic nuclear forces is evident from recent experiments.[7]

Nuclear charge symmetry implies, at every incident energy and at each scattering angle, that $d\sigma(\pi^{+3}H) = d\sigma(\pi^{-3}He)$ and $d\sigma(\pi^{-3}H) = d\sigma(\pi^{+3}He)$. It follows directly that CS also implies that the superratio

$$R \equiv \left[\frac{d\sigma(\pi^+\ ^3H)}{d\sigma(\pi^-\ ^3He)}\right] \cdot \left[\frac{d\sigma(\pi^-\ ^3H)}{d\sigma(\pi^+\ ^3He)}\right]$$

is equal to one at all angles and energies. A relative measurement of the four cross sections in this expression for R performed under identical experimental conditions, rather than separate measurements of the individual absolute cross sections, has the important experimental advantages that the detector efficiency and especially the π^+ and π^- beam normalizations cancel. The only published measurement,[8] at T_π=180 MeV at laboratory angles from 40° to 90°, showed R to deviate from one, indicative of CS nonconservation; the statistical accuracy was only 7% since safety restrictions limited the amount of tritium that could be used, and the uncertainty in the measurement of the pressures of the gas targets gave rise to a systematic uncertainty of +3% to -6%. The experience gained in that experiment led to a new target-cell design, so that (a) seven times as much tritium could be used and (b) the target cells could be weighed accurately to determine more precisely the tritium-to-^{3}He atomic ratio.

The experiment was performed using EPICS at the Los Alamos Meson Physics Facility. We used five identical target cells of cylindrical shape, 12 cm in diameter and 23 cm high, with a wall thickness of 1.8 mm, made of special aluminum (alloy 2024-T3511) which has a small diffusion coefficient for tritium and a high tensile strength. Four of the cells contained the T_2, D_2, H_2, and ^{3}He samples; the fifth was evacuated and used as a sample blank. Thorough pressure and leak tests were made on the cells. The gas samples were ~3 moles each and the pressure in each cylinder was 3 MPa (30 atm). The number of atoms in each gas sample was determined by direct weighing as well as by pressure, volume, and temperature measurement. The ratio of the number of ^{3}H to ^{3}He atoms was determined to within 0.3%. The radioactivity of the tritium sample was 200,000 curies.

Measurements of π^+ and π^- elastic scattering were made at incident beam energies of 142, 180, and 220 MeV, spanning the region of the Δ(1232) resonance. The scattering angles were 40°, 60°, 80°, 90°, and 110°(lab). At each angle, we measured the π^+ yields from ^{3}He, ^{3}H, ^{2}H, ^{1}H, and the empty target with the spectrometer tuned for pion-tritium elastic-scattering kinematics. Usually, we performed several alternating runs with the ^{3}He and ^{3}H targets to check for consistency. This data set was followed by measurements using the deuterium and empty targets with the spectrometer set for pion-deuterium kinematics for beam normalization. Occasionally, we included a hydrogen normalization run as well. The above sequence was repeated for π^-.

The relative run-to-run beam monitoring was done using two ionization chambers and a pion-decay monitor located downstream of the target. The relative beam intensity, together with the drift-chamber efficiency of the detector section of the EPICS spectrometer, was checked using elastic pion-aluminum scattering from the target-cell walls. The reproducibility of the relative beam normalization was 1.5% and the uncertainty in the determination of the drift-chamber efficiencies was 0.5%. From the relative normalized yields, we obtained the ratios ρ_1 and ρ_2, where

$$\rho_1 = \frac{Y(\pi^{+3}H \rightarrow \pi^{+3}H) - Y(\pi^+ bgd)}{Y(\pi^{+3}He \rightarrow \pi^{+3}He) - Y(\pi^+ bgd)} \cdot \frac{N(^3He)}{N(^3H)} \quad \text{and}$$

$$\rho_2 = \frac{Y(\pi^{-3}H \rightarrow \pi^{-3}H) - Y(\pi^- bgd)}{Y(\pi^{-3}He \rightarrow \pi^{-3}He) - Y(\pi^- bgd)} \cdot \frac{N(^3He)}{N(^3H)} .$$

The yields Y are the numbers of events recorded per unit beam monitor in the momentum interval that covers elastic scattering, corrected for drift-chamber inefficiencies; N(^{3}He) and N(^{3}H) are the numbers of ^{3}He and ^{3}H atoms in the targets. The background, which consisted mainly of pions inelastically scattered from the target walls and a few muons from the decay of pions in the spectrometer, was measured using the hydrogen and the empty targets. In the worst case, the background under the peak was less than 30%. At 110° we also used the D_2 target for background evaluation. Use of the various backgrounds yielded the same values for ρ_1 and ρ_2 to within 2%. The superratio is then obtained as the direct product $R=\rho_1\rho_2$. The results are shown in Fig. 1. Included in this figure are the data points of Ref. 8 at T_π=180 MeV, indicated by the crosses, without including the systematic uncertainty of that measurement. It can be seen that there is agreement between the two sets of results.

The simple ratios, which should be equal to one if CS is valid,

$$r_1' \equiv \frac{d\sigma(\pi^{+3}H)}{d\sigma(\pi^{-3}He)}\cdot\frac{d\sigma(\pi^- d)}{d\sigma(\pi^+ d)} \quad \text{and} \quad r_2' \equiv \frac{d\sigma(\pi^{-3}H)}{d\sigma(\pi^{+3}He)}\cdot\frac{d\sigma(\pi^+ d)}{d\sigma(\pi^- d)}$$

were obtained by normalizing the π^+ and π^- beams using πd elastic scattering. If one assumes that the ratio $r_d \equiv d\sigma(\pi^+ d \rightarrow \pi^+ d)/d\sigma(\pi^- d \rightarrow \pi^- d)$ is equal to one, then r_1' and r_2' become the "simple" ratios defined and discussed in Ref. 8. The advantages of using r_1' and r_2' rather than r_1 and r_2 are better experimental accuracy and simplicity in the interpretation of the results. The importance of r_1' and r_2' lies in the fact that they can be used to make a model independent comparison of the n and p matter distribution in ^{3}H and ^{3}He, which is the subject of a forthcoming paper[9]. There is a published measurement (Ref. 6) at T_π=143 MeV, which shows r_d to be equal to one to within 6%. The data in that experiment were normalized using old πp elastic-scattering data which have since been found to be slightly in error[10]; our new evaluation of r_d shows it to be even closer to unity. The results for r_1' and r_2' are shown in Fig. 2, along with those for R. Included are the results from Ref. 8 at T_π=180 MeV for r_1 and r_2 converted to r_1' and r_2'; the error bars shown include a 5% uncertainty in normalization.

The differential cross sections for π^+ elastic scattering on ^3H and ^3He were obtained by calibrating the π^+ beam using the accurate (5% absolute) π^+d elastic-scattering data from SIN.[11] The π^- cross sections were obtained using r_d=1.00 in the calibration procedure as well. Our new results at T_π=142 and 180 MeV, as well as those from Ref. 8, are shown in Fig 3. The data at T_π=220 MeV are sparse and are presented in Table I only.

The original measurement of the superratio (Ref. 8) has stimulated considerable speculation regarding the origin of the deviation of R from unity. Barshay and Sehgal[12] have proposed a geometrical model for the trinucleon structures with a short-range three-nucleon correlation and a charge-symmetry-violating Coulomb distortion. They predict that R=1.8 at T_π=180 MeV and θ_L=110° (the chain-dashed curve in Fig. 1), in gross disagreement with our new results. Kim[13] has suggested that the deviation of R from unity might be due to a multiquark compound resonance. A consequence of this argument is that R has a resonance behavior as a function of the incident pion energy. It can be seen Fig. 1 that this is apparently not the case. Kim, Krell, and Tiator[14] have calculated elastic pion scattering using a local optical potential, and have argued that the direct Coulomb force could be responsible for the large CS violation seen in Ref. 8. At T_π=180 MeV, the version of this calculation which includes no Coulomb effect between the protons in ^3He (the solid curve) deviates markedly from the data both at small and large angles, and the version which includes the Coulomb effect (the dotted curve) deviates markedly from the data near θ_{cm}=90° (as well as at small angles). At T_π=142 and 220 MeV, both versions are in gross disagreement with the data. Finally, Werntz and Cannata[15] have suggested that a large part of the deviation of R from unity can be related to the difference in binding energies of the like nucleons in ^{3}H and ^{3}He, but the final results of their calculation have not yet been published.

Kim, Kim, and Landau[16] have explored in detail the effect of Coulomb distortion of the nuclear force on R. They use a momentum-space optical-potential code that features an improved description of off-energy-shell, recoil, binding, and kinematic effects, and most importantly, includes spin-flip scattering which arises from realistic nuclear structure and an exact treatment of the Coulomb force. Their results describe reasonably well our cross-section data for π^+ and π^- elastic scattering on ^{3}H at T_π=180 MeV as well as earlier data on ^{3}He at T_π=200 MeV.[17] The calculation of Ref. 16 of the Coulomb effects on the superratio is the best available. Nevertheless, its predictions for the superratio do not agree with our data, in particular at 40°, 50°, and 110° (see Fig. 2).

Thus, no calculation published to date has been able to explain our results for the deviation of R from unity. Possible explanations for the measured deviation include (1) $A(\pi^+p)\neq A(\pi^-n)$, where A is the spin-flip and/or the spin-non-flip amplitude for elastic scattering; (2) $F(^3H)\neq F(^3He)$, where F is the matter form factor[18] (this could be due to a small difference between the coupling constants $g(pp\pi^0)$ and $g(nn\pi^0)$[19] as a result of $\Delta m\neq 0$); and (3) a CS-violating three-body interaction.[20] Quite likely, the explanation lies in some combination of the above. Moreover, the deviation of R from one is mainly due to r_2' being greater than one. In accordance with the sensitivity of CS tests given in the beginning of this Letter, r_2' depends on $3\Delta m$ while r_1' depends only on Δm. Also, the quantitative explanation of the data must include the different proportions of spin-flip and spin-non-flip scattering for π^{+3}H and π^{-3}H.

In summary, we have obtained extensive data for the superratio, as well as for the simple ratios, for pion elastic scattering on ^3H and ^3He at three incident energies spanning the energy region of the Δ resonance. In all cases, both R and r_2' are greater than one, while r_1' is consistent with one. No extant model predicts values for R (and r_2') which agree with our results; in particular those models which have attempted to explain the results with Coulomb effects alone fail to reproduce our results at small and/or large angles. We conclude that the marked deviation of R from unity <u>at all angles and energies</u> implies the nonconservation of charge symmetry in the strong interaction.

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Table I. Differential cross sections (in mb/sr) in the center of mass for π^+ and π^- elastic scattering at T_π=220 MeV.

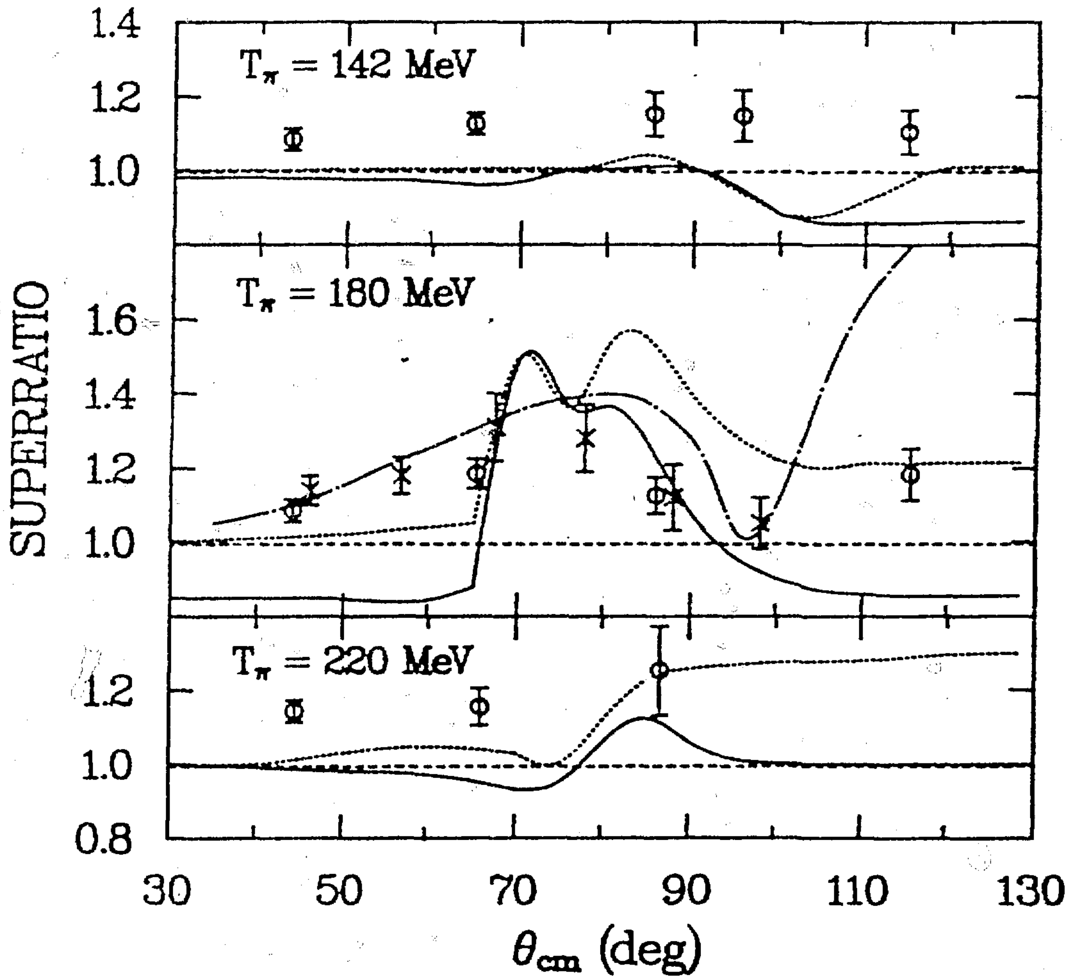
θ_π (lab)	Cos $\theta_{c.m.}$	$\pi^{+3}H$	$\pi^{-3}H$
40°	0.71	7.8 ± 0.6	10.5 ± 0.8
60°	0.41	0.69 ± 0.06	0.45 ± 0.03
80°	0.06	0.10 ± 0.01	0.08 ± 0.01

Figure Captions

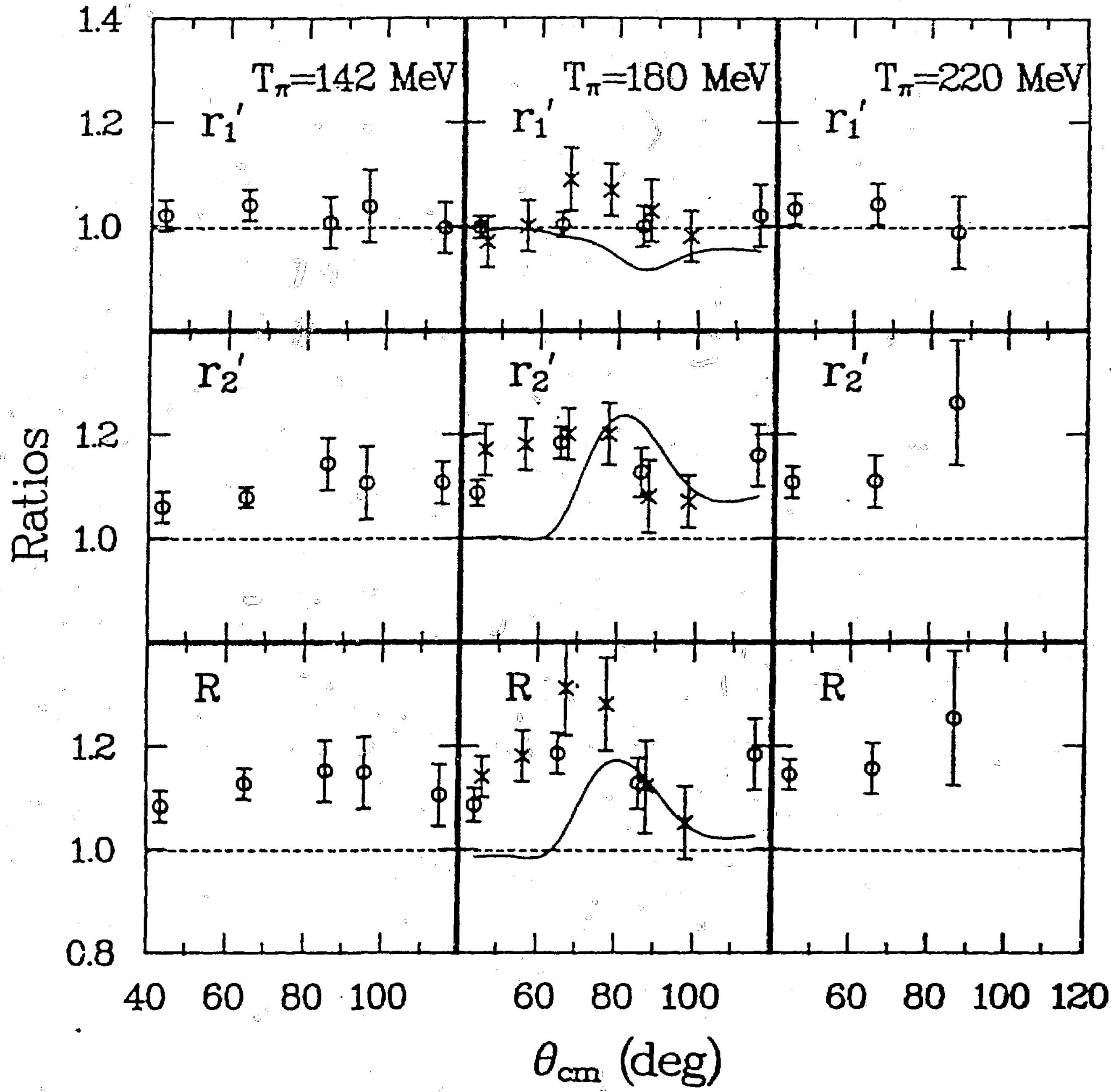
Fig. 1. The measured values of the superratio R at T_π=142, 180, and 220 MeV. Also, shown by crosses, are the data from Ref. 8 at T_π=180 MeV, displaced from the present data (open circles) by two degrees for clarity. The solid and dotted curves are the theoretical predictions of Ref. 13; the chain-dashed curve is that of Ref. 11.

Fig. 2. The measured values of the charge-symmetric ratios r_1' and r_2', together with those for R, as in Fig. 1. The solid curves are the theoretical predictions of Ref. 16. Conservation of CS implies that $R=r_1'=r_2'=1$; this is shown by the dashed lines.

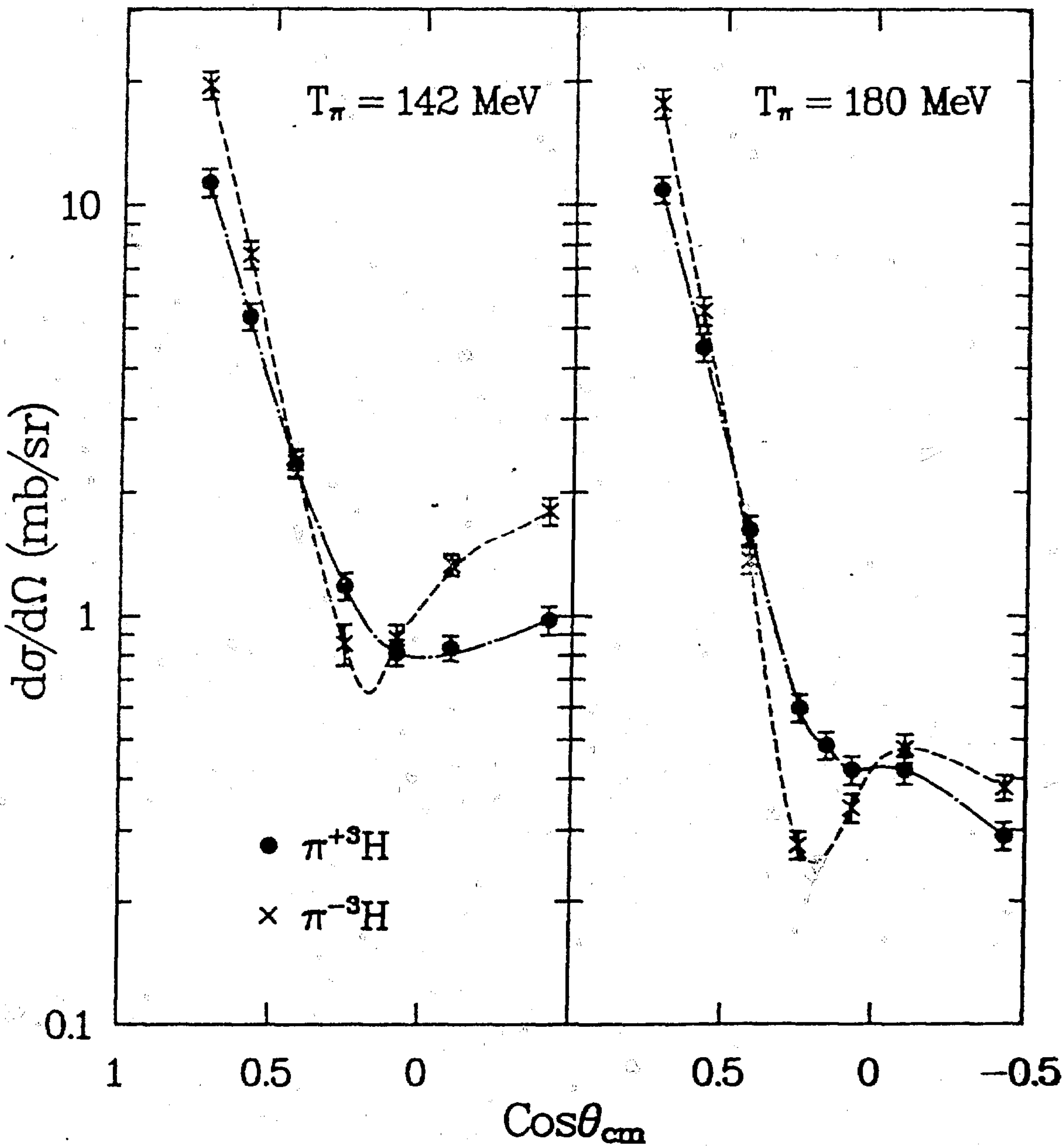
Fig. 3. Differential cross sections in the center of mass for π^+ and π^- elastic scattering on ^3H at T_π=142 and 180 MeV. Included are the data points from Ref. 8 at a few angles where the present experiment has none. The dashed and chain-dashed lines are drawn to guide the eye.



T$_\pi$ = 142 MeV
T$_\pi$ = 180 MeV
T$_\pi$ = 220 MeV
SUPERRATIO
1.4
1.2
1.0
1.6
1.4
1.2
1.0
1.2
1.0
0.8
30
50
70
90
110
130
θ_{cm} (deg)



Tπ=142 MeV
Tπ=180 MeV
Tπ=220 MeV
r1'
r2'
R
1.4
1.2
1.0
0.8
Ratios
40
60
80
100
120
θcm (deg)



$T_\pi = 142$ MeV
$T_\pi = 180$ MeV
10
1
0.1
$d\sigma/d\Omega$ (mb/sr)
$\pi^{+3}H$
$\pi^{-3}H$
1
0.5
0
0.5
0
−0.5
$Cos\theta_{cm}$