CM-P00057811

Archives

Ref. TH. 897

IS ISOSPIN INVARIANCE VIOLATED IN πN BACKWARD SCATTERING?

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A B S T R A C T

Isospin invariance implies an inequality for πN cross-sections. We point out that, if the low energy charge exchange experiments are taken literally, they seem to show widespread violation of it in πN backward scattering.

68/532/5 - TH. 897

19 April 1968

1. INTRODUCTION

In a previous paper ¹⁾ we studied the isospin dependence in the $\pi N \rightarrow \pi N$ data. We then obtained the unexpected and surprising result that the charge independence (CI) triangle is experimentally flat in backward πN scattering.

We shall here, in more detail, study backward scattering, using the available direct measurements, together with the recent detailed phase shift analyses done at CERN ²⁾ and Saclay ³⁾. The phase shift analysis of Roper et al. (0-700 MeV) ⁴⁾, which was used in Ref. ¹⁾, is known to be inaccurate in the upper energy region. Furthermore, new measurements of the charge exchange process have been published.

In the following we shall first (Section 2) discuss the accuracy by which one can test triangle inequalities experimentally and define a quantity which is useful for this purpose. We discuss here also the very low energy region, where the flatness of the CI triangle follows from simple low energy dynamics. In Section 3 we discuss the electromagnetic corrections which, within the present theory, are negligible in backward scattering above 50 MeV. In Section 4, we analyse the backward experimental data, and observe that the points systematically lie outside the limit of charge independence. The phase shift analyses, which assume CI, therefore find solutions which are very close to the limit. Finally, in Section 5, we discuss the different alternative conclusions one can draw from these results, and the possibility of violation of isospin invariance is emphasized.

2. THE FLAT CHARGE INDEPENDENCE TRIANGLE

An exactly flat, or zero area CI triangle, means in terms of amplitudes that these have the same or opposite phase (see Figs. 1a and 1b). The triangle inequalities are then satisfied as equalities.

The area of the triangle is

$$S = \frac{1}{2} \sqrt{-\lambda(\sigma^+, \sigma^-, 2\sigma^{\text{ex}})} , \quad (1)$$

where

$$\lambda(x, y, z) = x^2 + y^2 + z^2 - 2xy - 2xz - 2yz . \quad (2)$$

As a measure of the flatness one could use S . The errors of S are however not of the same order as those of the cross-sections. A better measure is therefore the following quantity, which is simply related to the area:

$$F = \sqrt{1 + 2\lambda(y^+, y^-, 2y^{\text{ex}})} , \quad (3)$$

where the y^i are the branching ratios

$$y^i = \sigma^i / (\sigma^+ + \sigma^- + \sigma^{\text{ex}}) . \quad (4)$$

This quantity F , which we call "flatness" is equal to one for a flat CI triangle and zero for a triangle with maximal area ("normalized" by keeping $\sigma^+ + \sigma^- + \sigma^{\text{ex}}$ constant). If the triangle inequalities are violated F is > 1 . In a triangular diagram for branching ratios⁵⁾ (see Figs. 2-4) F is graphically represented as the radius from the centre of the circle defining the physical region.

For $F \approx 1$ we have

$$F \approx 1 + \lambda(y^+, y^-, 2y^\infty) = 1 - 8 \left(\frac{|A_1 A_3|}{|A_1|^2 + 2|A_3|^2} \right)^2 \sin^2(\varphi_1 - \varphi_3), \quad (5)$$

where A_{2T} and φ_{2T} are the isospin amplitudes and their phases. From this expression we see that we have exact flatness if A_1 , A_3 or $\sin(\varphi_1 - \varphi_3)$ is zero. However, since F is proportional to the square of sine, it is still very close to zero for small relative phases $\varphi_1 - \varphi_3$.⁶⁾

This is of importance at very low energies below the $\Delta(1236)$ resonance. Here all phases are small and the imaginary parts of the amplitudes are small. Therefore the relative phase is small or close to 180° and consequently the CI triangle very close to flat. Again, around 200 MeV, the $T = 3/2$ amplitude dominates due to the resonance and from the factor $(|A_1 A_3|)/(|A_1|^2 + 2|A_3|^2)$ we see that $F \approx 1$. Thus we see that up to 200 MeV the flatness follows from simple low energy dynamics. We have thus the much stronger constraint on the data ($F \approx 1$) from which the charge exchange cross-section can be computed from the elastic cross-sections. This is from the phenomenological point of view a great simplification of the low energy data. The electromagnetic effects violate this condition, but in backward scattering only at very low energies. (See Section 3.)

However, above 200 MeV this simple argument does not hold. Here there are contributions from both $T = 1/2$ and $T = 3/2$ resonances superimposed on a background. Thus, the A_1 and A_3 are of comparable magnitude and the relative phase need not be close to 0 or 180° . Therefore the observation of the flatness is here the most interesting, especially as there exist measurements of both elastic and charge exchange differential cross-sections. Therefore we can, in addition to using phase shift analysis, study the flatness directly with the data.

3. ELECTROMAGNETIC CORRECTIONS

Unfortunately there exists no complete theory which, in a unified way, takes account of all the electromagnetic corrections in πN scattering. In addition to first order Coulomb effects one can add 7) Coulomb phase shifts 8), inner Coulomb corrections 9), the phase space factor due to the $\pi^- \pi^0$ mass difference, relativistic corrections 10) and Coulomb barrier effects. The dominating contribution comes from the first order Coulomb corrections. In backward scattering all Coulomb corrections are negligible except at very low energies below 50 MeV. Here the phase space factor for the charge exchange process is of almost equal importance as the Coulomb scattering for the elastic scattering. The Coulomb amplitude interferes constructively with the strong interaction (dominantly S wave). This brings the branching ratios well inside the limit (see the dotted curves in Figs. 2, 5 and 6). The phase space factor, on the other hand, enhances σ^{ex} and brings the points almost back to the limit (middle dashed curve in Figs. 2, 5 and 6).

Between 50 and 190 MeV the interference from Coulomb scattering brings the points outside the limit, but very slightly so, the greatest deviation being at 80 MeV, ($\cos \theta = -1.0$) where $F = 1.006$. Above 190 MeV, on the other hand, the Coulomb effects make F smaller, but the decrease is less than 0.005. The phase space factor similarly decreases F , since it enhances σ^{ex} , but again by a negligible amount.

We conclude that electromagnetic corrections to backward scattering are very small above 50 MeV and any significant violation of the triangle inequalities implies that either the present electromagnetic corrections are insufficient by several orders of magnitude or SU_2 symmetry is broken.

4. THE ANALYSIS OF THE BACKWARD DATA

The data, which we have used, are on the one hand the cross-sections computed from the phase shift analyses done at CERN ²⁾ and Saclay ³⁾, and on the other hand the published direct measurements ¹¹⁾ ¹²⁾, ¹³⁾ close to backward scattering.

In Fig. 2 the backward ($\cos \theta = -1$) branching ratios obtained from the phase shift analyses are shown. The points from the CERN analysis are joined to the curve. The Saclay points are marked by the crosses. As we see the points are on the boundary up to a little above 600 MeV, and both analyses agree very well. Above this energy the points go off the circle and the two analyses do not agree any more. The Saclay points are much bumpier than those of CERN, which is due to the fact that the Saclay analysis is done for every energy separately, while the CERN energy dependent phases are smoothed over energy by dispersion relations. The disagreement between the two analyses can easily be understood by looking at the data. The cross-sections, especially σ^- and σ^{ex} dip strongly at $\cos \theta \approx -1$. Thus, any extrapolation to backward scattering must here be very uncertain. We have therefore dashed the curve in this region.

The behaviour of the curves above 450 MeV is different from those obtained from the phase shift analysis of Roper et al., (see Ref. ¹⁾). There the backward branching ratios deviated from the boundary already at 450 MeV and showed no sign of "turning back" at 600 MeV.

The curve is seen to oscillate between the points $N_{1/2}$ and $N_{3/2}$. These points correspond to the dominance of the $T = 1/2$ and $T = 3/2$ channels respectively. The turning points correspond to the different resonance regions. The $T = 1/2$ resonances around 600 MeV bring the points close to $N_{1/2}$ while the $\Delta(1920)$ brings the points

close to $N_{3/2}$ for a remarkably wide energy region 900-1400 MeV. At still higher energies the ratio between σ^+ and σ^- is between five and ten ^{14),15)}. This implies that the points must lie in the right-hand part of the diagram. Unfortunately backward charge exchange data of reasonable accuracy are missing ¹⁶⁾ at these energies.

In Figs. 3 and 4 we have plotted the relative phases between the two isospin amplitudes $\varphi_1 - \varphi_3$ and the relative phase between the elastic amplitudes $\varphi^- - \varphi^+$ as predicted by the CERN phase shift analysis. We see that $\varphi_1 - \varphi_3$ is far from being close to 0 or 180° in the resonance region. Here the flatness follows from the smallness of the factor $(|A_1 A_3|)/(|A_1|^2 + 2|A_3|^2)$ in (5). Again the relative phase $\varphi^- - \varphi^+$ is as large as 15° in the resonance regions. At 50 MeV it jumps from 0 to 180° . We wish however to emphasize that the errors on these relative phases must be enormous, since as we shall see, the data points lie outside the region allowed by CI, which would correspond to imaginary relative phases.

In Figs. 5 and 6 we show the branching ratios at $\cos \theta = -0.95$ and $\cos \theta = -0.85$. Here there is a contribution from the spin-flip process $|g|^2$, which adds incoherently to the non-spin-flip process $|f|^2$. The curves for $|f|^2$ separately are very close to the boundary and thus the deviation of the curve from the circle is mainly due to the averaging over spins. The points must though still be inside the circle. (This can be seen graphically or by using the Schwartz inequality ¹⁷⁾.) However, below 600 MeV $|g|^2$ is, according to phase shift analysis, small compared to $|f|^2$. Therefore the curves are still very close to the boundary.

The advantage of plotting the curves for $|f|^2 + |g|^2$ slightly off the backward direction is that now we can compare them directly with the data, without extrapolation to $\cos \theta = -1.0$ or knowledge of the polarization and spin rotation parameters. The knowledge of the latter for all three charge channels are necessary in order to be able to experimentally separate $|f|^2$ and $|g|^2$ without phase shift analysis.

Looking at the data points, we see that they lie systematically outside the allowed region up to 600 MeV. For every charge exchange data we have plotted one point and the data from elastic scattering are interpolated to the same energy and $\cos \theta$. In Figs. 5 and 6 we have not plotted some of the older or less accurate charge exchange measurements. Of these there would be a few points which would lie slightly inside the circle but the error regions are considerably larger than those in Figs. 5 and 6 (cf. Fig. 9). The error bars in Figs. 5 and 6 are those of the branching ratios with the largest and smallest error. To all errors given in the experiments we have added a 5% error in order to take into account the normalization errors. This is perhaps pessimistic since part of the normalization errors should cancel in the branching ratios. In any case this causes only a slight increase in our errors since the main error comes from the charge exchange data, where the quoted errors are sometimes as high as 30%. With a few important exceptions (Lind et al., and Chiu et al.) the charge exchange data are given in terms of coefficients of a cosine or Legendre function expansion. In computing the errors of the cross-sections from these we have assumed that the errors are uncorrelated. We should also point out that the branching ratios are of course not linearly related to the cross-sections. Therefore, the errors in the branching ratios are not directly proportional to those of the cross-sections. This is important especially for a branching ratio close to one. However, for our purpose, the branching ratios and their errors are more useful than the cross-sections themselves.

Since the experimental points lie systematically outside the allowed region, it is easy to understand that phase shift analyses find a solution which is very close to the boundary. In phase shift analysis CI is assumed and thus the curves are forced to be inside the circle. This is presumably also the main reason why phase shift analysts tend to get high χ^2 s if they do not considerably increase the errors of the charge exchange data or more drastically disregard completely some of these data. The latter is often done with the

charge exchange data at 313 MeV ¹¹⁾ (Lind et al.), where we find the most significant violation. This is the only experiment which detects the neutron and is therefore especially in backward scattering the most accurate experiment. Of course there may be some systematic error source in this experiment. Lind et al. pointed out that their data were barely compatible with a triangle inequality. However they extrapolated to $\cos \theta = -1.0$, whereby the errors become considerably larger than if the test is done at the angles of the data points.

The inconsistency at the lowest energies, has also been pointed out by Donald et al. ¹⁸⁾. They show that the very low energy total charge exchange cross-section data are systematically too large compared to the phase shift analysis prediction. There are only two experiments which give the differential as well as the total cross-section. We have therefore only two points in this energy region (31 and 40 MeV). This inconsistency at the lowest energies is related to the difficulty to determine the S wave scattering lengths. There is considerable disagreement between the different calculations. The values given by Lovelace ²⁾ correspond at zero energy to the branching ratios given by the starting point of the dashed curve along the circle. (The lower dashed curves include electromagnetic corrections as discussed in Section 3.)

The points at 150 and 170 MeV (from the data of Ashkin et al. ¹¹⁾) also lie slightly outside. This has also been pointed out previously by Schnitzer and Salzman ¹⁹⁾ who reexamined the discrepancy between π^-p scattering and dispersion relations found by Puppi and Stanghellini ²⁰⁾.

At 220 MeV there is a clear disagreement between the two experiments (Ashkin et al., and Deahl et al. ¹¹⁾, see Fig. 9). We have taken the average of these and as error taken the spacing between the two points.

In Figs. 7 and 8 the "flatness" F [see Eq. (3)] is drawn as a function of energy for the same data as in Figs. 5 and 6. From these diagrams the systematic violation of the inequality is particularly clear.

In Fig. 9 we have plotted all published charge exchange data at $\cos \theta = -0.95$. The older or less accurate data which are not used in the other plots are drawn with dashed error bars. The curve is from the CERN phase shift analysis and is seen to lie higher than the data in the first resonance region. We notice however that the charge exchange data above 500 MeV seem to be in fairly good agreement with the phase shift analysis, although we found violation of the inequality. Looking at the elastic cross-sections one finds that here the phase shift analysis predicts that the measured π^-p elastic cross-sections would be too large.

5. CONCLUSIONS

We conclude that purely statistically it is extremely unlikely that so many points from eight different charge exchange experiments should systematically be outside the allowed region, or at least on one side of the phase shift analysis predictions. Therefore there must either be widespread systematical errors in the data or isospin invariance is violated. Let us examine the different alternative conclusions one can draw from our results.

- 1) The violation of the triangle inequalities is assumed to be real. This is obviously a drastic result. It means either that electromagnetic effects are greatly enhanced in backward πN scattering or SU_2 symmetry is broken like the higher unitary symmetries. The experimental verification of all the consequences of isospin invariance are not as well experimentally tested as is usually believed. The best support comes from the multiplet structure of particles, from forbidden reactions like $dd \rightarrow dd\pi^0$ ²¹⁾, and from reactions which proceed through only one isospin channel as $pd \rightarrow H^3 + \pi^+$ and $pd \rightarrow He^3 + \pi^0$ ²²⁾. For reactions proceeding through more than one isospin channel, where interference terms between isospin amplitudes appear, the best data are just in πN scattering. In a recent accurate measurement ²³⁾ of $\pi^+ p$ and $\pi^+ d$ total cross-sections there is also some evidence of violation of CI. And in the reaction $\pi p \rightarrow \Sigma K$ the flatness of the CI triangle has been a puzzle for long ²⁴⁾, especially in the Σ backward direction.

Since the triangle inequalities are only a necessary but not a sufficient condition we cannot give a figure for the magnitude of this violation. It may be larger than what the deviations from the inequality indicate.

- 2) The CI triangle is assumed to be exactly flat. Looking at the curves obtained from phase shift analysis this possibility is suggestive. If CI is assumed it implies a phase relation between the amplitudes. However, this is much more serious than the previous alternative. Writing a dispersion relation for the logarithm of the amplitude one has a relation between the phase and the modulus of the amplitude. Then, from knowledge of the phase one can compute the modulus, which would imply that also these would have to be equal at all energies ²⁵⁾. This would imply that the elastic cross-sections would have to equal which is clearly in contradiction with experiment.
- 3) The violation of the inequality is assumed to be due to bad experiments. A systematic error in the charge exchange measurements giving too large cross-sections below 50 MeV and too small above the first resonance could bring the points inside the limits. New experiments to measure accurately the charge exchange will hopefully answer this question.

Further theoretical study of electromagnetic corrections to πN scattering and possible dynamical enhancements of them also seems called for. Chew-Low model calculations ²⁶⁾ have indicated that these could be much larger than usually supposed.

ACKNOWLEDGEMENTS

Many thanks are due to Drs. J.S. Bell and C. Lovelace for helpful discussions and to Dr. C. Lovelace for helping me to find all the references to the low energy experiments. I also wish here to record my thanks to Professor N. Svartholm (Göteborg) and to Dr. J. Kalckar (Copenhagen) for valuable criticism of my earlier work on CI and for their encouragements for further study. It is also a pleasure for me to acknowledge the hospitality shown to me by Professor J. Prentki at the Theoretical Study Division of CERN and the financial support from the Finnish National Council for Sciences.

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FIGURE CAPTIONSFigure 1 :

- a. The CI triangle.
- b. The flat CI triangle in the complex plane.

Figure 2 :

The branching ratios for backward scattering ($\cos \theta = -1.0$) with varying energy obtained from the phase shift analysis of CERN (curve) and Saclay (crosses).

Figure 3 :

The relative phase between the isospin amplitudes $\varphi_1 - \varphi_3$ as predicted by the CERN phase shift analysis.

Figure 4 :

The relative phase between the elastic amplitudes $\varphi^- - \varphi^+$ as predicted by the CERN phase shift analysis.

Figure 5 :

The branching ratios at $\cos \theta_{\text{cms}} = -0.95$ obtained from the phase shift analyses and from the direct measurements.

Figure 6 :

As in Fig. 5, but at $\cos \theta_{\text{cms}} = -0.85$.

Figure 7 :

The flatness F (see Section 2) as a function of energy at $\cos \theta_{\text{cms}} = -0.95$.

Figure 8 :

As in Fig. 7, but at $\cos \theta_{\text{cms}} = -0.85$.

Figure 9 :

The charge exchange data at $\cos \theta_{\text{cms}} = -0.95$ up to 600 MeV. The curve is obtained from the CERN phase shift analysis.

a

b

$$A^- = \sqrt{6^-} e^{i\varphi} \quad \sqrt{2} A^{ex} = \sqrt{26^{ex}} e^{i\varphi}$$

$$A^+ = \sqrt{6^+} e^{i\varphi}$$

Fig.1

Fig. 2

Fig. 3

Fig. 4

Fig. 6

Fig. 7

Fig. 8

Fig. 9