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Exotic Electromagnetic Currents: Present Status

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We present a critica1 discussion of the empirical status of the assumed isospin and C, T invariance properties of the hadronic electromagnetic current. In particular, we review the implications of recent experiments designed to test these assumptions in the pion photoproduction and radiative capture reactions. stating clearly the theoretical assumptions necessary to draw conclusions on the transformation laws from the observed cross-sections. We conclude that the magnitude of a possible isotensor contribution to the $\gamma N\Delta$ vertex is consistent with zero the possible upper limit being about 3% relative to the allowed isovectorterm. This represenis the first test of the $|\Delta I| \leq 1$ rule. other than for the electric charges. in any elementary particle process. Further. the most recent data on the radiative capture reactions are consistent with T-invariance and the photoproduction data. in agreement with the results found in other processes. which we summarize briefly.

Apresentamos uma discussào critica da situação empirica das propriedades de isospin e de invariância C e T assumidas para a corrente eletromagnética dos hadrons. Em particular revisamos as implicações das experiêcias recentes destinadas a testar tais propriedades na fotoprodução de pions e nas reaçòes de captura radiativa, deixando claro quais as hip teses te ricas necessárias para que se possa. a partir das seções de choque observadas. tirar conclusões a respeito das leis de transformaçáo. Concluimos que a magnitude de uma possivel contribuição isotensorial ao vertice $\gamma N\Delta$ é consistente com zero, sendo que o limite superior aceitável é da ordem de 3%. Este resultado representa o primeiro teste da regra $|\Delta I| \leq 1$ que não seja para as cargas elétricas, sendo aplicável em qualquer processo envolvendo par-tículas elementares. Além disso, os dados mais recentes sobre as reaçòes de captura radiativa consistentes com a invariância T e com os dados de fotoprodução, o que está de acordo com os resultados observados em outros processos. que sumariamos brevemente.

1. Introduction

By exotic electromagnetic currents we simply mean components of the current J_μ which behave under symmetry transformations differently fro the charge, and in the present instance we shall be concerned with two possible examples of these. namely $I = 2$ ("isotensor") and C-violating terms. In particular we shall be concerned with recent experiments designed to detect. or set upper limits on. the presence of such terms in the reactions

$$\gamma N \rightleftarrows \pi N \tag{1}$$

in the energy region of the $\Delta(1236)$ resonance. However, while doing this it is important to keep in mind the context provided by our knowledge of other reactions. Thus, in the case of C-violating terms, experimental study of a wide variety of processes other than those with which we are presently concerned has led to no evidence for such effects in electromagnetic interactions. On the other hand, in the case of isotensor terms, whose presence would violate no established principles, we have no knowledge at all from experiments in other processes[1]. I will therefore begin my discussion by considering the tests for $I = 2$ terms on the assumption that T is conserved, turning to the question of its possible violation later. I shall concentrate on the theoretical ideas underlying the tests, and the sort of limits they lead to using present data. More detailed discussion of the experiments quoted, and questions concerning the extraction of neutron cross sections from experiments on deuterium, can of course be found in the original' papers to which we will refer.

2. Test for I = 2 Assuming C(T) Conservation

The aim of these tests is to look for isotensor contributions to the vertex $\gamma N \to \Delta$ in $\gamma N \rightleftarrows \pi N$. On protons, this resonance excitation is known to be predominantly in the magnetic dipole amplitude

$$_{p}M^{3}_{1+} = \sqrt{\frac{2}{3}}\left\{M^{3}_{1+} - \sqrt{\frac{3}{5}}\,M^{2}_{1+}\right\}, \tag{2a}$$

where M^{3}_{1+}, M^{2}_{1+} are isovector, isotensor amplitudes respectively. On neutrons,

$$_{n}M^{3}_{1+} = \sqrt{\frac{2}{3}}\left\{M^{3}_{1+} + \sqrt{\frac{3}{5}}\,M^{2}_{1+}\right\}, \tag{2b}$$

so that in the absence of $I = 2$ terms

$$M^{2}_{1+} = 0, \qquad {}_{p}M^{3}_{1+} = {}_{n}M^{3}_{1+}\,. \tag{3}$$

It is convenient to parametrize violations of these by introducing t, x, where

$$M^{2}_{1+} = tM^{3}_{1+}\,, \qquad {}_{n}M^{3}_{1+} = (1 + x)\,{}_{p}M^{3}_{1+}\,. \tag{4}$$

If T is conserved, x, t are real, and $x, t = 0$ if $|\Delta I| \leq 1$. In simple resonance forms, x and t are constant and

$$\Gamma_{\Delta^0 \to n\gamma} = (1 + x)^2\ \Gamma_{\Delta^+ \to p\gamma}\,. \tag{5}$$

We shall assume them constant over the region of the resonance (200 MeV < E_γ(lab) < 400 MeV), although in general they will be slowly varying. From the copious data on the proton reactions

$$\gamma + p \rightarrow \pi^+ + n,\ \pi^0 + p,$$

we can obtain information on $_{\Delta^+ \rightarrow p\gamma}$, but obviously to make the comparisons suggested above we require neutron data.

3. Charged Pion Photoproduction

We shall first consider the reactions

$$\gamma + p \rightarrow \pi^+ + n \qquad (6a)$$

$$\gamma + n \rightarrow \pi^- + p, \qquad (6b)$$

for which most data is available. It was initially suggested[2] that the use of deuterium targets should be avoided by studying the radiative capture reaction

$$\pi^- + p \rightarrow \gamma + n \qquad (7)$$

and using detailed balance to make the necessary comparisons. That is, using

$$\frac{d\sigma}{d\Omega}(\pi^-) \equiv \frac{d\sigma}{d\Omega}(\gamma n \rightarrow \pi^- p) = \frac{1}{2}(q^2/k^2)\frac{d\sigma}{d\Omega}(\pi^- p \rightarrow \gamma n), \qquad (8)$$

where q, k are the centre of mass photon, pion momenta, respectively.

Alternatively, one may deduce the neutron cross sections from deuteron cross sections using calculated deuteron corrections. A third alternative is to study the π^-/π^+ ratio on deuterium. This has two advantages. Firstly, the ratio is much less sensitive to deuteron corrections than the individual cross sections themselves. Secondly, it is to this ratio that the parameters x, t are sensitive. Thus if the ratios are used, the results on x, t are relatively insensitive to the magnitudes of the π^+ cross sections of reaction (6a), so that uncertainties due to discrepancies between different measurements of reaction (6a) are largely avoided. However, even given the necessary data on reactions (6a, b) there is still a problem, because for both $\pi^\pm$ photoproduction, large non-resonant backgrounds are expected which make width extraction from limited data difficult. This is indicated in Fig. 1: the breakdown of the total cross section into its multipole components for the π^+ case is shown. This sort of breakdown results both from theoretical models (see below) and from multipole analysis of the data[3] The

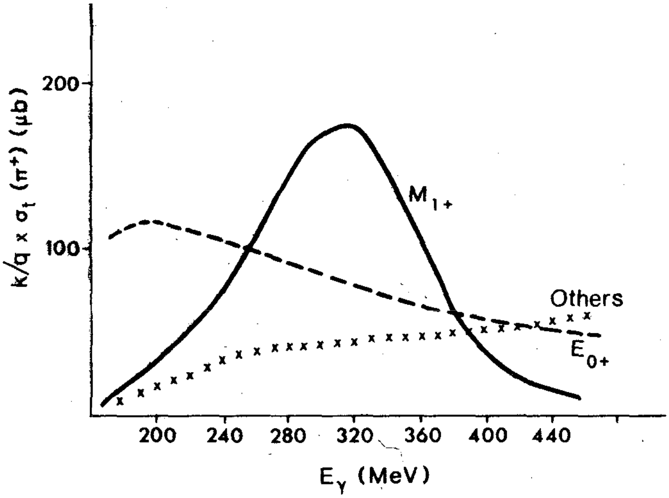


Fig. 1 - Approximate breakdown of the total cross-section for π^+ into its various contributions

method of dealing with this usually used is the so-called Dip Test in which the idea is to form a quantity from which, if the $|\Delta I| \leq 1$ rule holds the resonance must cancel. Thus if a resonance signal is detected, the rule must be violated. Since this test is crucial to the interpretation of recent data we will discuss it in some detail, considering three approaches.

3.1 The quantity it was suggested should be examined is[4]

$$\Delta(W) = \frac{k}{q} \{\sigma_t(\pi^-) - \sigma_t(\pi^+)\}. \tag{9}$$

By use of the total cross section, interference between the resonant and other J, P states is eliminated, and the factor k/q is a kinematical factor which removes at least the S-wave thereshold dependence. If we rewrite A exposing the resonant terms', we have

$$\Delta(W) = \frac{64\pi}{9}\sqrt{\frac{3}{5}}\,\mathrm{Re}\,\{\sqrt{15}\, M^0_{1+} M^{3*}_{1+} - M^1_{1+} M^{2*}_{1+} + M^2_{1+} M^{3*}_{1+}\} + $$

$$+ \text{ (non-resonant, non-interfering background).} \tag{10}$$

If $M^2_{1+} \neq 0$, then the term $M^2_{1+} M^{3*}_{1+} = t\,|M^3_{1+}|^2$ can produce a resonant signal, i.e. a dip (or peak). Can such a dip be produced if the I = 2 term is not present? There is no reason why the background should show it and the only other term remaining if $M_{1+}^{2} = 0$ is the first. From T-invariance and unitarity, while M_{1+}^{3} has the δ_{33} scattering phase, the isoscalar multipole M_{1+}^{0} is essentially real ($\rho_{31} \sim 2°$ at resonance) so that this interference term should vanish at resonance, and so cannot produce a dip there. If M_{1+}^{0} were large it could produce a wiggle, but as we shall see, even this is unlikely.

3.2 Let us now examine this matter in a more concrete way in the context of Fixed-t Dispersion Relations. If we decompose the T-matrix into the usual four CGLN invariant amplitudes[6]

$$T = \sum_{i=1}^{4} \bar{u} M_i u A_i(s, t, u), \tag{11}$$

they obey relations of the form

$$A_i(s, t) = \text{Born terms} + \frac{1}{\pi} \int_{s_0}^{c} ds' \, \text{Im} \, A_i(s', t) \left[\frac{1}{s' - s} \pm \frac{1}{u' - u} \right]. \tag{12}$$

There are three important points about these relations:

(a) – They are rigorous relations. Further over the resonance region there are no problems with the partial wave expansion over the t-range required (assuming Mandelstam analyticity).
(b) – Apart from the known Born terms, the integrals are over energies in the physical region, so that only measurable quantities are involved[7].
(c) – At high energies, $A_i(t) \sim s^{\alpha(t)-1}$, so that the relations converge for all $\alpha(t) < 1$ (Ref. 8).

Obviously these relations are both general and restrictive and any solution to be taken seriously must be compatible with them. Let us now discuss their application. For this, it is convenient to divide up the integral into three ranges, i.e.

$$A_i(s, t) = \text{Born} + \int \Delta \text{ region} + \int \text{Higher Resonances} + \int \text{Regge region}. \tag{13}$$

Simple Models – Born + Δ Region

In this region, the dominating (but not the only) contributions are those shown in Fig. 1A.

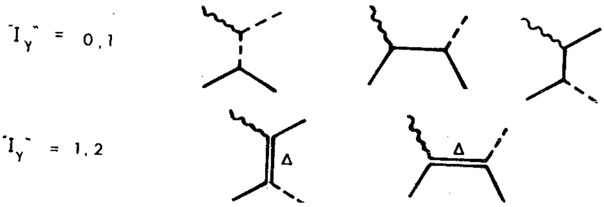


Fig. 1A

The effects of introducing both isotensor and *T*-violating terms into this model, and its use in analysing data, have been discussed in some detail elsewhere[9]. Here we are just concerned with the effects of $I = 2$ terms (assuming T) on the behaviour of **A.** The results of this are shown in Fig. 2.

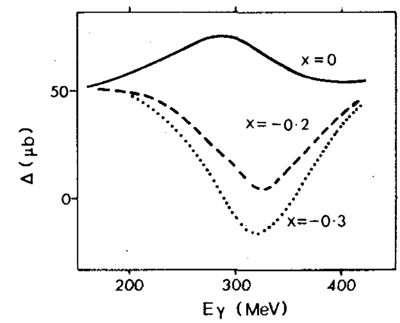


Fig. 2 - Predictions of **A** from the Born + A,, model of Ref.4.

and we note both the dip occurring in the two isotensor cases, and the comparatively smooth shape of the no isotensor curve.

Of course these curves are the results of a model. However it is a model which incorporates **all** the nearest singularities, so that we would expect it to be reasonably reliable for the shapes of the curves, although clearly distant contributions can raise or lower the curves somewhat by slowly varying amounts. This expectation is borne out by explicitly considering the two terms we have neglected.

(a) The Regge Region

From high energy experimental work we know that the effective $\alpha(t) \sim 0$ so that the dispersion relations converge rapidly. It is surely reasonable to assume that contributions from this region can have no effect on local structure in the A region.

(b) The Higher Resonance Region

A thorough study of this point has been made by Devenish, Lyth and Rankin[10]. These authors have first analyzed the data for the reactions

$$\gamma + p \rightarrow \pi^0 + p,\ \pi^+ + n,$$
$$\gamma + n \rightarrow \pi^- + p,$$

in the resonance region to estimate the various couplings. They have then fed these into the dispersion relations, working in a resonance saturation approximation, to examine the effect on the predictions in the A„ resonance region. The resulting predictions for A, both with and without the higher resonances included, are shown in Fig. 3.

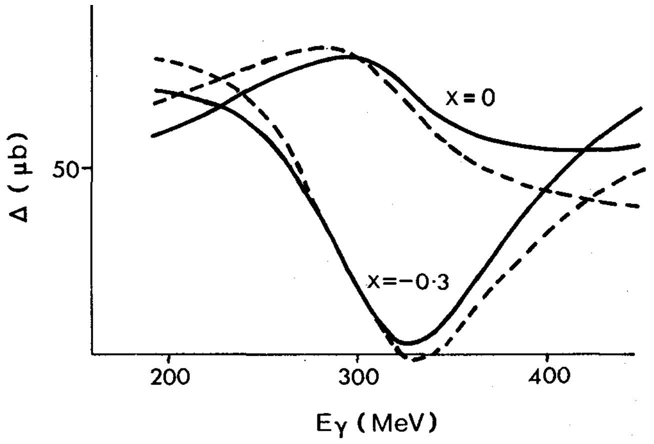


Fig. 3 - Predictions of the model of Devenish *et al.*[10]. Solid lines: Born + Δ_{33} terms only. Dashed lines: higher resonances included.

3.3 The third way of looking at this is to take a data set which exhibits a dip, and try to fit it without an I = 2 term. The clearest example of work of this kind is that of Noelle and Pfeil'' whose results we summarize. If the absence of I = 2 is assumed, the relation

$$-A^{\pi^-} = A^{\pi^+} - 2\sqrt{2}\,A^0 \qquad (14)$$

follows. In the Born + A region models, the isoscalar amplitudes A^0 are given to a good approximation by the Born terms. Assuming this, Noelle and Pfeil first compared the results of using the multipole analysis results[3] for A^{π^+} with the results obtained using the simple Bom + A results of Sanda and myself[4]. As can be seen in Fig. 4, the results are very similar.

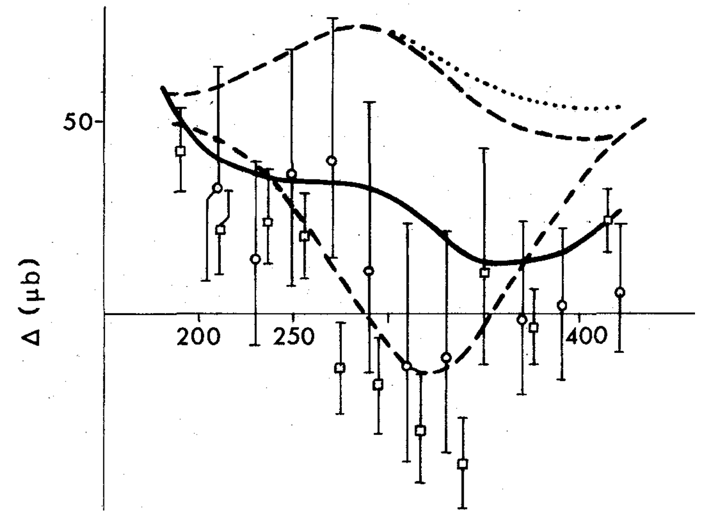


Fig. 4 - Results on A from the paper of Noelle and Pfeil". Lines shown are the results of Ref. 4 for x = 0 (. . . .) and x = – 0.3 (– – – –). Also for x = 0 with A^{π^+} taken from multipole analysis (– – – –) and the fit of Noelle and Pfeil (—— –), see text.

They then, retaining the multipole analysis results for the π^+ amplitudes. represented the isoscalar multipoles by polynomials (a cubic in the most important case of E^0_{0+}) and fitted to a data set, ignoring the restrictions of dispersion relations. The data set used – which I stress is obsolete and discussed only for purposes of illustration – is shown in Fig. 4. The important point is that the data points with smallest errors, which will dominate any fit, indicate a dip structure. What happens if you fit them without I = 2 terms, ignoring dispersion relations?

The result is shown by the solid curve in Fig. 4, it does not show a dip structure and lies far from the points with small errors around 300 MeV (the simple Born + A model with x = – 0.3 is superimposed for comparison). What is more telling is the E^0_{0+} amplitude which has been demanded to produce even this small degree of structure: this is shown in Fig. 5 labelled NP. In contrast, the Born term alone is shown, and a calculation including the other small non-resonant terms is shown (BDW[12]). Also shown is

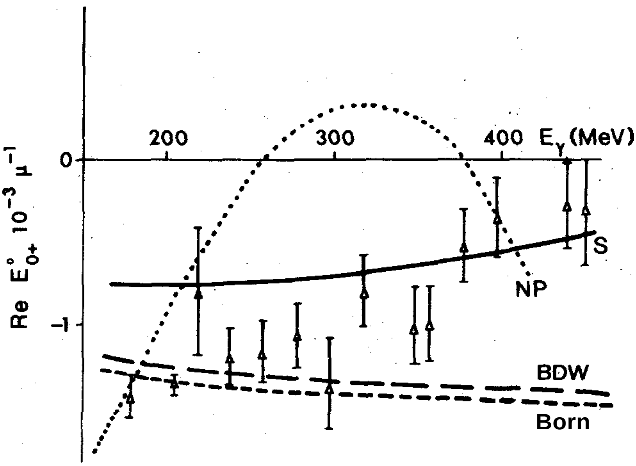


Fig. 5 - E^0_{0+} from the Noelle and **Pfeil fit** (....) (central solution) compared to various **dispersion relation** results, see text.

the result of a calculation by **Schwela**[13] which effectively includes a subtraction constant which can be regarded as **allowing** for the effect of distant singularities. It **is** clear that even the amount of structure in A given in this **fit** – which is hardly a dip – **has** been produced at the price of what looks like a **serious** violation of the fixed-t dispersion relations which, as we have noted, rest on a rather **secure** foundation.

(We note in passing that it has been pointed **out**[11] that some energy variation of E^0_{0+} is **called** for by π^-/π^+ ratio data in the threshold **region**. The points shown in Fig. 5 are in fact taken from a multipole analysis of a data set which does not **indicate** an isotensor component ($\Delta(W)$ **is** smoothly varying) and which also includes the threshold region **data**[14]. It **is** clear that the energy variation **required** is **not** nearly so rapid as in the NP curve, and is obviously much **less** disturbing).

Conclusions on the Dip Test

On the basis of the preceding discussion, it is in my view reasonable to conclude that

(a) an isotensor excitation M^2_{1+} leads naturally to a dip in the quantity $\Delta(W)$, and

(b) such an effect cannot be produced in the absence of $I = 2$ terms (unless we abandon the rigorous fixed-t dispersion relations), so that the ocurrence of such a dip is clear evidence for an $I = 2$ term. Further,
(c) the Born + A model prediction for A in the absence of $I = 2$ terms (which is a no free parameter prediction) is probably reasonably reliable for the shape (up to about 400 MeV above which second resonance contributions begin to become important) although it can be moved up and down somewhat by slowly varying amounts.

CGLN Model of M_{1+}

Before going on to discuss the data, we note that in the dispersion relation part of the above discussion, we have assumed that the dispersion relations do not determine the resonance couplings, and that these must be determined from the data. Of course if the assumptions made are stringent enough, the resonance coupling will indeed be predicted. The classical model of this type is that of Chew et *al.*[6] (CGLN). In this work the $|\Delta I| \leq 1$ rule was assumed, but it is easy to modify the model to drop this assumption. The assumptions of the model (besides T-invariance) are

(a) Project from the fixed-t relations partial wave equations for M_{1+} etc. These are formally valid for $E_\gamma \lesssim 450$ MeV only, but are used to infinity.
(b) In inhomogeneous terms, retain the Born terms only;
(c) Assume elastic unitarity to ∞.

In the static limit, you then have the solution

$$M_{1+}^3 = m = \frac{\mu}{2f}\,\frac{k}{q^2}\,e^{i\delta}\sin\delta, \qquad (\delta \equiv \delta_{33}).$$

To make this solution unique under the above assurnptions, one must assume boundary conditions, either $\delta(\infty) = 0$; or $\delta(\infty) \leq \pi$, $M_{1+}(\infty) = 0$. These assumptions then also imply

$$M_{1+}^2 = 0.$$

On comparing with data, the resultant $_pM_{1+}^3$ is roughly correct, although the shape seems wrong[3]. Thus if one assumes $M_{1+}^3 \sim m$, upper limits on M_{1+}^2 can be obtained from proton data alone, as noted by Gittelman and Schmidt[1']. However, this procedure is highly model dependent (as these authors noted), and to obtain solutions which reproduce the proton data with non-zero isotensor resonance excitation, and $M_{1+}^3 \neq m$ one can either simply modify the boundary conditions[4] or abandon assumption (b)[10]. These questions are discussed in detail by Devenish *et al.*[1] Finally, on this point we note that a recent paper[16] claiming that certain data are incompatible with fixed-t dispersion relations for the isovector amplitudes is again based on the assumption of the uniqueness of the CGLN result for M^3_{1+}. Thus their conclusion is again highly model dependent, as a glance at the above assumptions shows.

Comparison with Total Cross Section Data

We now return to the Dip Test, and to the experimental data on A(O) The results of the PRFN collaboration[17] for this quantity are shown in Fig. 6. As can be seen, the results exhibit a clear dip, and a dispersion relation fit gave values of x = –0.26, t = –0.15 (Ref. 18).

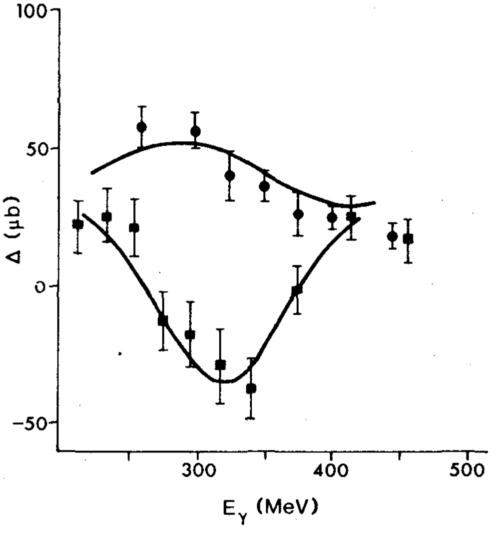
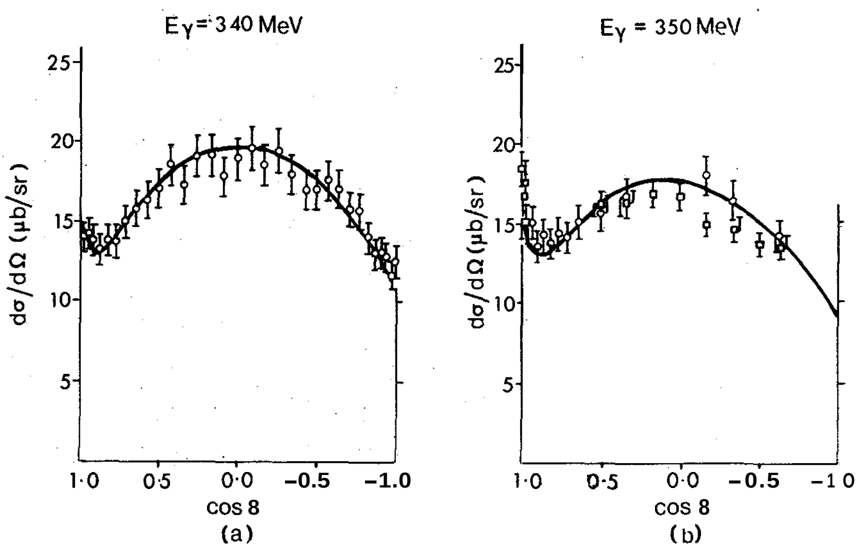


Fig. 6 - Experimental results on $\Delta(W)$. Solid circles: Fujii et al. [20]. Solid Squares: PRFN[17].

In contrast, the results of the ABBHHM collaboration[19] on the π reaction (6b), and the π^-/π^+ ratio measurements of Fujii *et al.*[20] and von Holtey *et al.*[21] all lead to a smooth behaviour for A. The results of Fujii *et al.*[20] are shown in Fig. 6. It is clear that these three experiments, which are in agreement with each other, are compatible with no, or very little, isotensor term.

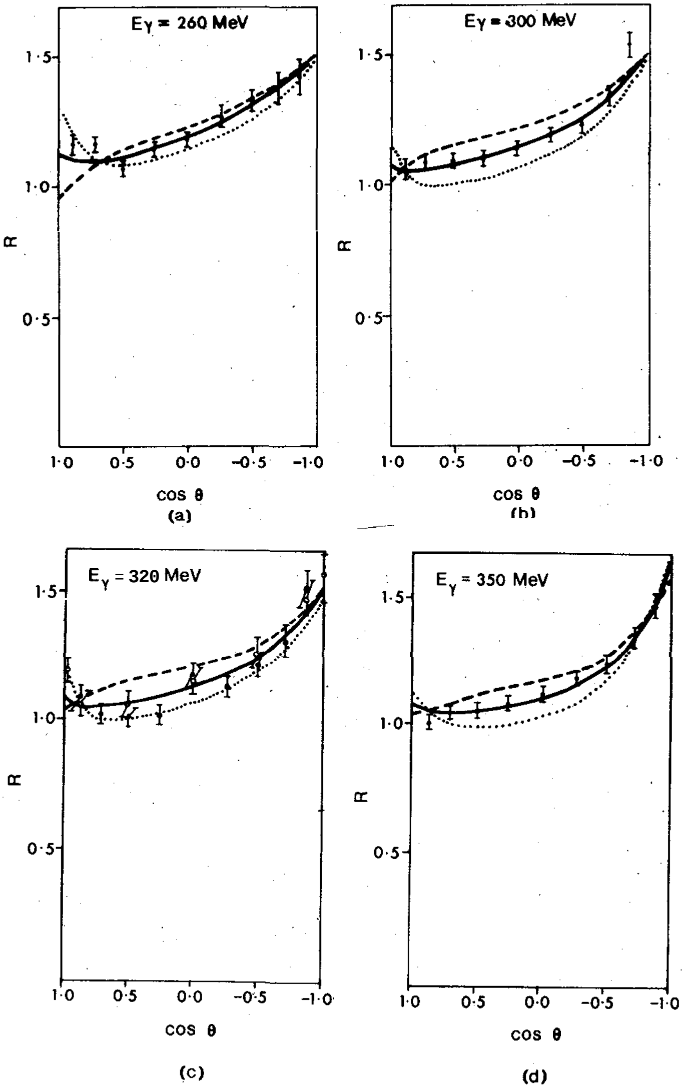
A Dispersion Relation Analysis

In order to obtain a more precise result from the measurements of the π^-/π^+ ratio, Donnachie and I[22] have performed an analysis based on the dispersion relations discussed earlier. As well as allowing the resonance contributions to vary to fit the data, slowly varying terms with free parameters were incorporated into both the *E*,, and M_{1-} multipoles in each charge state. We performed three fits with the parameter t in Eqn. (4) fixed at values of + 0.05, 0.00 and –0.05 respectively. The other six parameters were varied to give the best possible fit to the π^+ and π^-/π^+ ratio data over the energy range 200 < *E*, < *400* MeV. A sample of the π^+ differential cross section data used[23–25] is shown in Fig. 7(a, b). As



Figs. 7(a, b) - **Differential** cross-section data for π^+ photoproduction. Open circles: Fischer et ai. [23,24] Open Squares: Betourni et al.[25].

hãs been stressed by **Nefkens**[26], there is a small discrepancy between the **Orsay**[23] and **Bonn**[24,25] experiments in the angular region 90 – 120". This is insignificant for our present purpose, since the parameter t is sensitive not to the π^+ differential cross section, but to the π^-/π^+ ratio. The results of the fits to this latter quantity are shown in Figs. 8 (a-d), and it is clear that the values $t = \pm 0.05$ are incompatible with the data. On the basis



Figs. 8(a-d) - π^-/π^+ data at 260, 300, 320 and 350 MeV. Solid circles: Fujii *et al.*[18]. Open circles: Van Holtey *et al.*[19]. Solid line: $t = 0.00$ (best fit). Dashed line: $t = 0.05$, dotted line $t = -0.05$.

of these curves we concluded that, within this model, the data sets an upper limit of about 3% on the ratio of isotensor to isovector resonance excitation (assuming T invariance).

4. Neutron Pion Photoproduction

The test suggested here[2] is the comparison of the reactions

$$\gamma + p \to \pi^0 + p, \tag{15a}$$

$$\gamma + n \to \pi^0 + n. \tag{15b}$$

(It is best if both are studied on deuterium). The essential point here is that both simple models, and data plus a multipole analysis[3], lead to the conclusion that reaction (15a), unlike the $\pi^\pm$ reactions, is resonance do-

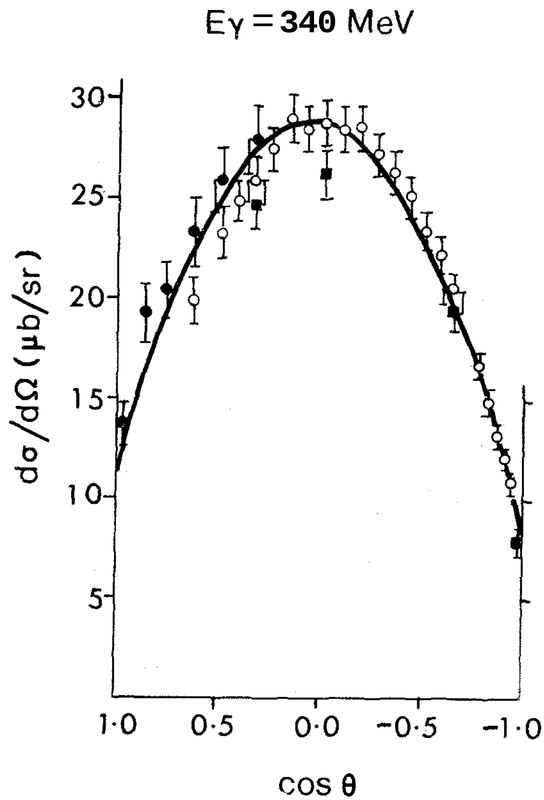


Fig. 9 - Differential cross section for $\gamma p \to \pi^0 p$ at 340 MeV. Open circles: Fischer *et al.*[38]. Closed circles: Hilger *et al.*[39]. Closed squares: Morand *et al.*[40].

minated. At 340 MeV, near the resonance position the angular distribution (Fig. 9) is close to the $(5-3\cos^2\theta)$ distribution expected from pure M_{1+}, and the resonance amplitude contributes roughly 95% of the total cross section. Obviously if the $\pi^0 n$ case is similar, as suggested by all the models I know of, the problem of analysis is trivial.

Turning to experiment, there was until recently no data available on reaction (15b) in the first resonance region, and one of the most important recent developments is that such measurements have now being carried out. The preliminary results of the Daresbury experiment[27] on the $\pi^0 n/\pi^0 p$ ratio over this energy region are shown in Fig. 10, and the preliminary

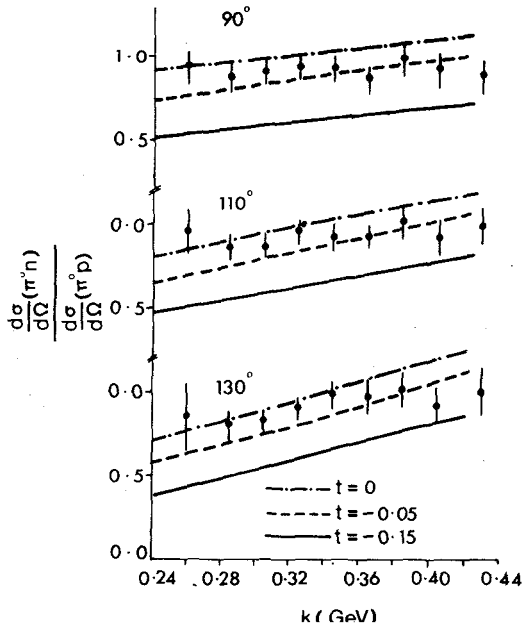


Fig. 10 - The measured $\pi^0 n/\pi^0 p$ ratios at 90°, 110" and 130°, compared with dispersion relation predictions (see text) for $t = 0.00$, −0.05 and −0.15.

results of a new Frasc ti experiment[28] are in agreement with these. The results are compared with the predictions of the fits to the π^-/π^+ ratio data with $t = 0.00, -0.05$ (Ref. 22), and the fit to the PRFN data[17] with $t = -0.15$ (Ref. 18). In drawing conclusions, one should of course bear in mind that the data are preliminary, and that we have ignored the possibility of deuteron corrections to the $\pi^0 n/\pi^0 p$ ratio. These might be somewhat more important than in the π^-/π^+ case owing to the possibility of interference effects in the final states not present in this latter case[2"]. Also the theoretical curves are somewhat preliminary[30], although this is unlikely to be significant (compared to the stated experimental errors) in the ratios at the angles shown in view of the resonance dominated nature of the reactions. However. ifwe put aside these reservations for the moment. it is clear that the data gives a very small upper limit on t This accords with the results of the DESY[19] Tokyo[20] and Bonn'' results on the π^- reaction (6b), suggesting that the PRFN data'' in the first resonance region is incorrect. In the next section therefore, when we wish to compare data on reaction (6b) with that on reaction (7), I shall not include the results of this latter experiment.

5. Tests for T-Invariance: Radiative Capture

The suggestion that the observed C-violation in $K_L^0 \to \pi^+\pi^-$ decay might be electromagnetic in origin[31] initiated an extensive search for C-violating effects in many electromagnetic processes. Some of the most important results of this search are

5.1 $K_L \to 2\pi$ Decays

The measured values of η_{+-} . η_{00} indicate that their difference is small and consistent with zero''. In this case the (2π) state would be purely $I = 0$. While this would not be forbidden if the C-violation were purely electrornagnetic in origin, there would be no reason to expect it.

5.2 η^0 Decays

(a) $\eta^0 \to \pi^0 e^+ e^-$

The occurrence of this decay in lowest order would be evidence for an $I = 1$ C-violation. The upper limit on the branching ratio is'' 4×10^{-4}.

(b) $\eta^0 \to \pi^+\pi^-\pi^0$

Early results gave a non-zero value for the $\pi^+\pi^-$ asymmetry in this decay. However, the most precise and recent measurement gives (-0.0005 ± 0.0022) (Ref. 33).

(c) $\eta^0 \to \pi^+\pi^-\gamma$

The most recent measurement of the charge asymmetry gives (0.005 ± 0.006) (Ref. **34).**

5.3 $n + p \rightleftarrows \gamma + d$

According to the model of Barshay[35] this is a test for a *T*-violating phase in the isovector $\Delta N\gamma$ vertex. Interpreted in this way. the experimental results give a value[36] for this phase of (4" ± 10).

The comparison of the reactions

$$\gamma + n \to \pi^- + p. \tag{16a}$$
$$\pi^- + p \to \gamma + n. \tag{16b}$$

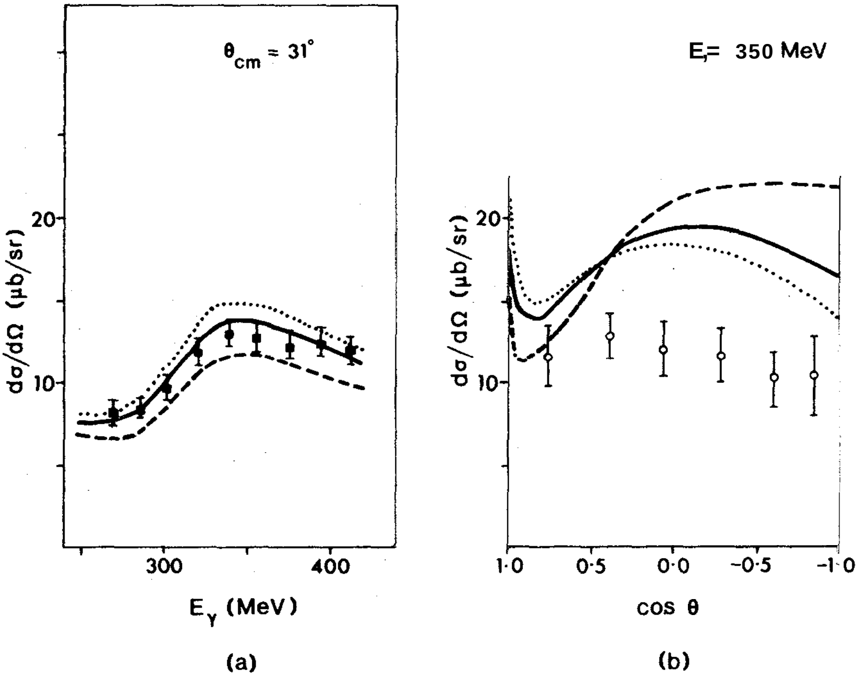
enables us to add a very sensitive test to this array[37]. Further, in contrast to the tests for $I = 2$ terms there is no need for complicated discussion. The result

$$\frac{d\sigma}{d\Omega}(\gamma n \to \pi^- p) \neq \frac{1}{2}\frac{q^2}{k^2}\frac{d\sigma}{d\Omega}(\pi^- p \to \gamma n) \tag{17}$$

unambiguously implies a violation of T-invariance.

This test is completely model independent (provided of course the necessary information on reaction (16a) can be extracted from deuterium data) Nonetheless, it is instructive to examine the test in a dispersion theory framework in order to assess its sensitivity. and to relate it to other processes If in this framework one retains only the dominating Born + A contributions, then the only way to introduce *T*-violating phases is in the vertices $\Delta^+ p\gamma$ and $\Delta^0 n\gamma$ We denote these by ϕ_p, ϕ_n respectively In general these phases can be different. but if the $|\Delta I|$ = 1 rule is assumed for the *C*-violating as well as the C-conserving current. then $\phi_p = \phi_n = \phi_1 = 4° \pm 10''$ from the results of the np → γd experiment cited above Further. if appreciable *T*-violating effects were introduced via other slowly varying terms – e.g the third and fourth terms of Eqn (13) – then there would be no reason for them to be localised to the energy region of the A resonance. and it would be difficult to understand the agreement between reactions (16a, b) in the energy region above the resonance[20] We therefore restrict ourselves to the model[39,9,22] in which *T*-violation is introduced into the dispersion relation models described in Section 3 2 by allowing non-zero values for the *T*-violating phases ϕ_p, ϕ_n only. In fact for the reactions considered, the crucial parameter is ϕ_n, since ϕ_p contributes only via the A pole in the crossed (u) channel. which is relatively unimportant compared to the corresponding (s)channel contribution For further details we refer to the original papers[9]

Some results from our most recent application of this model are shown in Figs. 11(a, b). In this calculation the fits to the π^+ and π^- π^+ ratio data



Figs. 11(a, b) - Predictions for the right hand side of Eqn. (17) for *T*-violating phase values of ϕ_n *U* 0° (solid line), ϕ_n *U K* 10" (dashed line) and ϕ_n *U* – 5° (dotted line). The radiative capture data shown is that of (a) Favier yt *al.*[26] and (b) Berardo *γt al.*[37]. These latter points should be raised by about 4% to allow for the fact that they were actually taken at 354 rather than 350 MeV.

described at the end of Section 3 were repeated for ϕ_n values of *K* 10" and – 5°, in addition to the T-conserving case ϕ_n *U* 0 already discussed. The curves show the resulting predictions for the right hand side of Eqn. (17) for each of the three cases. As can be seen the cross sections are very sensitive to the introduction of T-violation, except in the region of 65' where, according to the model, Eqn. (17) is satisfied whether T is violated or not.

Let us now turn to the comparison of these results, (and the π^0 photoproduction data in general) to the measured cross sections for the radiative capture reaction (16b). Of course, in doing this we should bear in mind the data used in obtaining the specific curves of Fig. 11. Thus the curve ϕ_n *U* 0 corresponds to the prediction for the cross section for the π^0 photoproduction reaction (16a) based on measurements on the $\pi^{\pm}$ photoproduction cross sections[23,25] and the π^-/π^+ ratio[20,21]. The data points used (see Figs. 7, 8) have typical errors of about 7% and 3% respectively. A more serious problem, stressed by Nefkens[26], is the discrepancy between the Bonn[Z5] and Orsay[23] π^+ cross sections for angles greater than 90". In Section 3, this was unimportant since the parameter t (Eqn. (4)) with which we were concerned was sensitive primarily to the π^-/π^+ ratio However, here it is more serious and must be borne in mind when considering capture data in this angular region. However, at smaller angles this problem does not arise, and in particular in the region 60"-70" where in our model the photoproduction and capture cross sections should agree even if T is violated, the two experiments[23,24] are in extremely close agreement.

On Figs. 10(a, b) we show the data on the reaction $\pi^- p \rightarrow \gamma n$ available when the above calculation was carried out. On the basis of these figures, Donnachie and I[22] concluded that the excitation curve of Favier et *al.*[40] at about 30" was only compatible with 7'-violating phases of the order of 10" or less, and that the preliminary angular distribution data of Berardo et *al.*[41] could not be accounted for by a 7'-violating phase of this order. We further concluded that, **within** *our* model, this latter data was incompatible with the photoproduction data used whether T was violated or not. This remark hinges primarily on the behaviour around 60°, and so is not affected by the discrepancy between the Bonn[Z4] and Orsay[23] experiments at wider angles mentioned above.

The data presented recently at the Daresbury meeting on tests for exotic electromagnetic currents and, subsequently, at the Bonn conference, have brought about a dramatic improvement in this situation. In addition to the 30" excitation curve discussed above, the Lausanne-Munich group have now presented[42] similar curves at 60" and at 90". Within our dispersion theory model, the 60" curve is an important consistency check on the data used, but the effects of a *T*-violating phase would be clearly seen at 90°. However, in both cases the $\pi^- p \rightarrow \gamma n$ cross-sections obtained are in excellent agreement with the π^- photoproduction cross-sections inferred from the π^+ cross-section measurements, and the π^-/π^+ ratio data, confirming the small limit inferred from the 30" data alone.

There are also new results on angular distributions at fixed energy, namely the final results of Berardo et *al.*[43] which replace the preliminary results at 354 MeV shown in Fig. 11(b), and the preliminary results of a new experiment by the UCLA group[44] at 305 and 405 MeV. The final cross-sections at 354 MeV are increased by amounts varying between 8 and 25% compared to the preliminary results reducing the theoretical problem illustratecl in Fig. 11(a). However they still lie lower than all the photoproduction experiments, and about 20% lower than the radiative capture results of the Lausanne-Munich group[42] at this energy. A few per cent of this discrepancy can perhaps be accounted for by the energy resolution as stressed by Nefkens[23]. However, it is clear that the situation at this energy is still not satisfactory.

On the other hand, the new results for the angular distributions at 305 MeV and 405 MeV present (for T-conserving theorists) a much more cheerful prospect, being in good agreement with the inverse photoproduction data. This is exhibited for the former energy in Fig. 12. This is a particularly

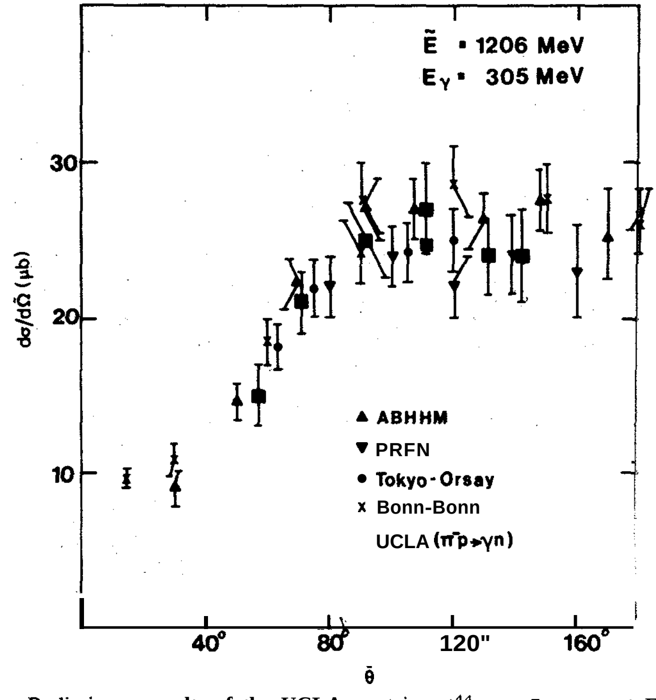


Fig. 12 - Preliminary results of the UCLA experiment[44] on $\pi^- p \to \gamma n$ at $E_\gamma = 305$ MeV compared to recent measurements of $\gamma n \to \pi^- p$ using detailed balance (Eqn. 8).

suitable energy to choose since, at 305 MeV, one is (a) very sensitive to any *T*-violating phase, but (b) insensitive to slight errors in the measured energy, since the cross sections are slowly varying at this point. Further there is at this energy reasonable agreement between this experiment and the Lausanne-Munich experiment, the differences between the two being about $(+4 \pm 3)\ \mu b$ at 60°, and $(+1 \pm 3)\ \mu b$ at 90°. Thus this angular distribution is impressive evidence for T-conservation in this process.

We thus conclude that despite the detailed difficulties at 355 MeV, there is no real evidence for T-violation in this process. Further a full theoretical analysis of these results ought to lead (in spite of the questions raised regarding the π^+ cross sections at angles greater than 90°) to a good limit on the T-violating phase, certainly no more than 10°.

6. Conclusions

The $|\Delta I| \leq 1$ rule for the hadronic electromagnetic current was first suggested in 1952[45]. The lack of experimental evidence for its validity was first stressed in 1966[8] and in 1967 I wrote[2]:

"In general, familiarity is held to breed contempt. In physics, it breeds acceptance; a proposition comes to be accepted either by experimental verification, or by remaining untested for a sufficiently long period of time. The above rule falls firmly into the second category".

The experiments discussed in this article, and particularly the new results reported at the Daresbury meeting and the Bonn conference, have rendered this sarcasm obsolete. Previous to these meetings, the position was that the PRFN data[17] on the π^- differential cross sections suggested the presence of an isotensor resonance excitation of about 15% (compared to the dominant isovector excitation), whereas the ABBHHM results[19] and the π^-/π^+ ratio results of the Tokyo[20] and Bonn[21] groups, suggested an upper limit of a few per cent. This latter result has now received further support from the results of the first experiments to be presented on the $\pi^0 n/\pi^0 p$ ratio[27,28] which again suggest a limit at the few per cent level, but in a more model independent way. This rests on the assumption that the $\pi^0 n/\pi^0 p$ ratio, like the π^-/π^+ ratio on deuterium, is relatively insensitive to the deuteron corrections, an assumption that it is of course necessary to check.

Turning to the question of T-violation, we are here of course not performing the first tests of a principie, but adding a further sensitive test to those already performed in other reactions. To do, this, we require experimental data on the radiative capture reaction (16b), and again important new results have recently become available [42,43,44] while there remain some problems, in particular concerning the angular distribution at

355 MeV, there is in general good agreement between the two reactions (16a, b). Thus there is at present no evidence for T-violation in this process, and further careful study of these results should lead to an impressive limit on the T-violating phase.

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