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Charge Symmetry Breaking in Neutron–Proton Scattering above Pion Production Threshold

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Abstract

We examine the effect of the coupled NΔ inelastic channel on charge symmetry breaking in the np system. Our calculation includes the effects of mass splitting for the nucleon and delta multiplets in the channel coupling potentials. The results suggest that such effects become increasingly important at about 500 MeV laboratory energy.

1. Introduction

At the present time there is considerable interest in searching for charge symmetry breaking (CSB) in few-body systems such as $\pi^{\pm}$d (Pedroni *et al.* 1978; Masterson *et al.* 1984), $\pi^{\pm}\,{}^3$He (Nefkens *et al.* 1984) and np (Abegg *et al.* 1986). We shall restrict our attention to the np system where a TRIUMF experiment recently revealed evidence for a new piece of the NN force. In the classification of Henley and Miller (1979) this new force is class IV, that is

$$V_{\rm IV} = (\boldsymbol{\tau}_1-\boldsymbol{\tau}_2)_z(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2)\,.\,\boldsymbol{L}v(r)+(\boldsymbol{\tau}_1\times\boldsymbol{\tau}_2)_z(\boldsymbol{\sigma}_1\times\boldsymbol{\sigma}_2)\,.\,\boldsymbol{L}w(r)\,. \qquad (1)$$

Experimentally, the observation was a nonzero value for $\Delta A \equiv A_{\rm n}(\theta)-A_{\rm p}(\theta)$ at the crossover angle [i.e. where the neutron analysing power $A_{\rm n}(\theta) = 0$]. At TRIUMF further measurements are proposed at 350 MeV, while at IUCF a more ambitious attempt to determine both ΔA and $C_{xz}-C_{zx}$ near the crossover angle has been underway for some time (Vigdor 1985).

The major results of the theoretical analysis up to now (Miller *et al.* 1986; Williams *et al.* 1987; Holzenkamp *et al.* 1987) are readily summarised. The dominant contribution to CSB at the crossover angle arises from the np mass difference at the vertices in π and ρ exchange. Photon exchange is relatively small, $\pi^0\eta$ mixing does not give a class-IV force in the NN system, and while $\rho^0\omega$ mixing does give a class-IV force its effects are small at crossover. [The Bonn potential (Holinde 1981) is an interesting exception at 188 MeV where Holzenkamp *et al.* (1987) found that $\rho^0\omega$ mixing contributes half of ΔA.] All estimates of the effect of two-pion-exchange (TPE) are that it is small, as one would expect given that TPE is predominantly isoscalar. However, the estimates of CSB in the TPE force have so far ignored the possibility of pion production. Our aim

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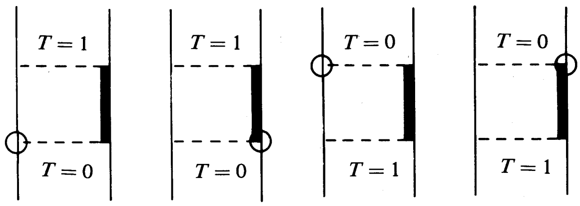

Fig. 1. The four two-pion-exchange graphs, involving NΔ intermediate states, which contribute to charge symmetry breaking in np scattering. The vertex where charge symmetry is broken is circled. In the case of $\eta\pi^0$ mixing the pion end must attach to the NΔ vertex.

here is to investigate the effect on CSB in the np system of the coupling to the inelastic NΔ channel, as illustrated in Fig. 1.

Our recent work on isospin breaking in the deuteron (Niskanen and Thomas 1987) and CSB in the np $\rightarrow$ dπ^0 reaction (Niskanen *et al.* 1987) has revealed a number of novel features of the coupled NN–NΔ system. For example, in the NN space the indication of a class-IV force is that $I = 0$ and 1 (and therefore that $S = 0$ and 1) are mixed. Tensor forces therefore play no role in CSB, nor does a class-III force proportional to $(\boldsymbol{\tau}_1+\boldsymbol{\tau}_2)_z$. On the other hand, if our interaction is generalised to depend on $(\boldsymbol{T}_1+\boldsymbol{T}_2)_z$ (where $\boldsymbol{T}$ is an NΔ transition isospin operator and its coefficient may include tensor forces), then we can generate an effective class-IV NN force through channel coupling. An interaction of this generalised class-III type is generated by mass splitting in the N and Δ multiplets at the ΔNπ vertex, and also by $\eta\pi^0$ mixing. Clearly a mechanism involving the Δ in this way should lead to an interesting energy dependence.

2. Theory

Our calculation uses the same extension of the coupled channels method by Green and Niskanen (1976) and Niskanen (1978, 1984) which has already been applied to isospin admixtures in the deuteron and to CSB in the np $\rightarrow$ dπ^0 reaction. The effect of mass splitting in the nucleon and delta multiplets is to yield new pieces in the NNπ and ΔNπ vertices, in particular

$$H_{\mathrm{NN}\pi} = -\delta\frac{f}{\mu}\boldsymbol{\sigma}.(\boldsymbol{p}+\boldsymbol{p}')(\boldsymbol{\tau}\times\boldsymbol{\phi})_z, \qquad H_{\Delta\mathrm{N}\pi} = -\delta\frac{f^*}{\mu}\boldsymbol{S}.(\boldsymbol{p}+\boldsymbol{p}')(\boldsymbol{T}\times\boldsymbol{\phi})_z, \tag{2}$$

where δ is taken to be $(m_{\mathrm{n}}-m_{\mathrm{p}})/(m_{\mathrm{n}}+m_{\mathrm{p}})$ for simplicity. (Some justification for using the same parameter to describe N and Δ mass splitting may be given on the basis of a simple quark model, since the underlying mechanism in both cases is $m_{\mathrm{d}}-m_{\mathrm{u}}$.) The coupling constants $f^2/4\pi$ and $f^{*2}/4\pi$ are respectively 0·081 and 0·35, and a monopole form factor of mass 700 MeV was used in the channel coupling potentials.

In previous work we have taken a conservative value for $\pi^0\eta$ mixing, namely $\langle\eta|H|\pi^0\rangle = -4000\ \mathrm{MeV}^2$ (McNamee *et al.* 1975; Coon *et al.* 1977), and we retain that here. The uncertainty in this matrix element is insignificant in view of two other considerations. First, the NNη coupling varies between $g^2_{\eta\mathrm{NN}}/4\pi = 0{\cdot}5$ and 3·68. Second, even though previous work, including our own, has stressed the $\eta\pi^0$ mechanism, *any* mechanism which leads to different π^0nn and π^0pp couplings will contribute in exactly the same way. Thus, our inclusion of $\eta\pi^0$ mixing should be taken as simply indicative of the effect of such a difference in coupling constants, no more.

By solving the coupled NN–NΔ equations including those channels which violate charge symmetry we obtain directly the S matrix element for NN singlet–triplet transitions. From this we construct the CSB amplitude $f(\theta)$ as

$$f(\theta) = \frac{1}{4k}\sum_{L=1}^{\infty} \frac{2L+1}{\{L(L+1)\}^{\frac{1}{2}}}(R^L_{L0,L1}+R^L_{L1,L0})P^1_L(\cos\theta), \tag{3}$$

with the standard parametrisation of the np scattering amplitude

$$M(\boldsymbol{k}_\mathrm{f},\, \boldsymbol{k}_\mathrm{i}) = \tfrac{1}{2}\{(a+b)+(a-b)\boldsymbol{\sigma}_1 . \boldsymbol{n}\,\boldsymbol{\sigma}_2 . \boldsymbol{n} + (c+d)\boldsymbol{\sigma}_1 . \boldsymbol{m}\,\boldsymbol{\sigma}_2 . \boldsymbol{m}$$

$$+(c-d)\boldsymbol{\sigma}_1 . \boldsymbol{l}\,\boldsymbol{\sigma}_2 . \boldsymbol{l} + e(\boldsymbol{\sigma}_1+\boldsymbol{\sigma}_2) . \boldsymbol{n} + f(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2) . \boldsymbol{n}\}\,; \tag{4}$$

$$\boldsymbol{l} = \frac{\boldsymbol{k}_\mathrm{f}+\boldsymbol{k}_\mathrm{i}}{|\boldsymbol{k}_\mathrm{f}+\boldsymbol{k}_\mathrm{i}|}, \qquad \boldsymbol{m} = \frac{\boldsymbol{k}_\mathrm{f}-\boldsymbol{k}_\mathrm{i}}{|\boldsymbol{k}_\mathrm{f}-\boldsymbol{k}_\mathrm{i}|}, \qquad \boldsymbol{n} = \frac{\boldsymbol{k}_\mathrm{i}\times\boldsymbol{k}_\mathrm{f}}{|\boldsymbol{k}_\mathrm{i}\times\boldsymbol{k}_\mathrm{f}|}. \tag{5}$$

[In equations (3)–(5) we have used the conventions of Bystricky *et al.* (1984).] Then ΔA is obtained in the standard way in terms of $\mathrm{Re}(b^* f)$. One technical point which should be added is that at high energies the convergence of the partial wave expansion for the one-pion-exchange contribution is poor. To speed convergence we used the analytic expression of La France and Winternitz (1980) for the Born approximation for J beyond 6. Finally, given the established sensitivity of CSB calculations to the NN phase shifts we actually used the phase shifts of Arndt *et al.* (1983). That is, following Gersten (1978), our S matrices were expressed in the form

$$\langle J1|S^J|J0\rangle = -\tfrac{1}{2}\sin 2\bar{\gamma}_J\, \mathrm{e}^{\mathrm{i}(\bar{\delta}_J+\bar{\delta}_{JJ})}. \tag{6}$$

Then our calculated (possibly complex) phase shifts $(\bar{\delta}_J, \bar{\delta}_{JJ})$ were replaced by those of Arndt and collaborators. All that is retained from the coupled channels calculation is the (possibly complex) mixing parameter $\bar{\gamma}_J$.

3. Results

Our results for ΔA at a range of energies through the Δ-resonance region are shown in Fig. 2. The arrows indicate the crossover point where measurements are most likely to be made first. In each case the solid curve omits the NΔ coupling altogether, while the dashed line is the full result of including NΔ coupling and CSB effects. Clearly the effects are very large, but this initial conclusion must be tempered with considerable caution as we shall see below.

First we examine the importance of the individual contributions. Fig. 3 illustrates the importance of individual terms at 477 MeV. The dot–dash curve includes only CSB effects generated by $\eta\pi^0$ mixing in the NN–NΔ channel coupling, while the short-dash curve includes all class-IV terms arising from mass splitting in the N and Δ multiplets. By summing these two one arrives at the full result (long-dash curve). For comparison the dotted and solid curves are respectively the results of Miller *et al.* (1986; CSB due to pion exchange only), and the present work in the approximation

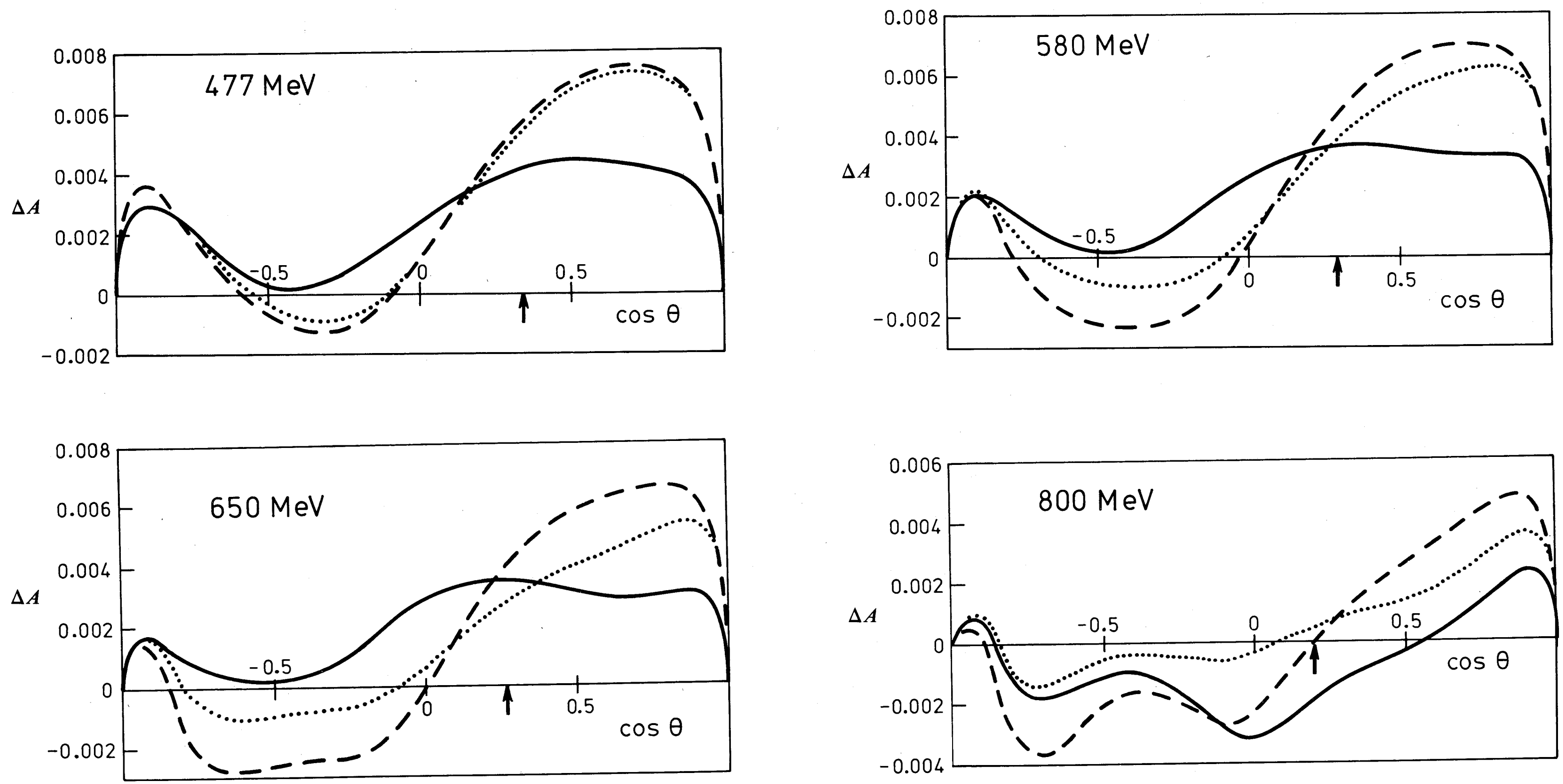

Fig. 2. Calculations of $\Delta A = A_n - A_p$ at the four neutron laboratory energies indicated. The solid curve does not include NΔ coupling, the dashed curve is the full calculation, and the meaning of the dotted curves is given in Section 3. The arrows indicate the crossover angle where measurements are most likely to be made.

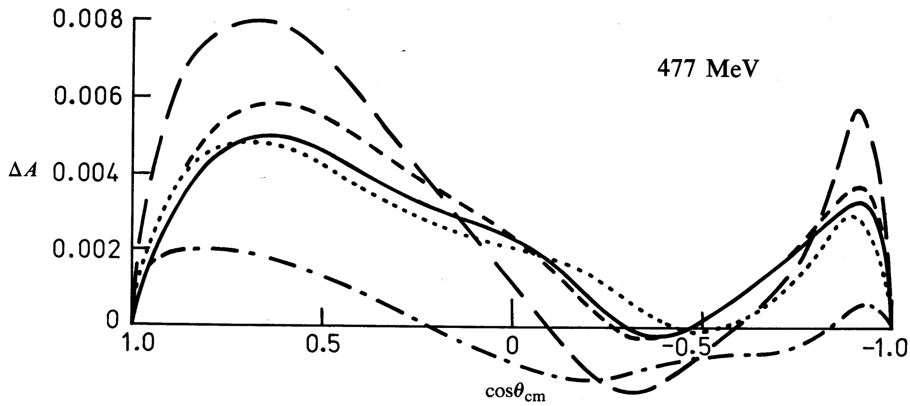

Fig. 3. Details of the contributions to ΔA at 477 MeV—the meaning of the curves is explained in Section 3.

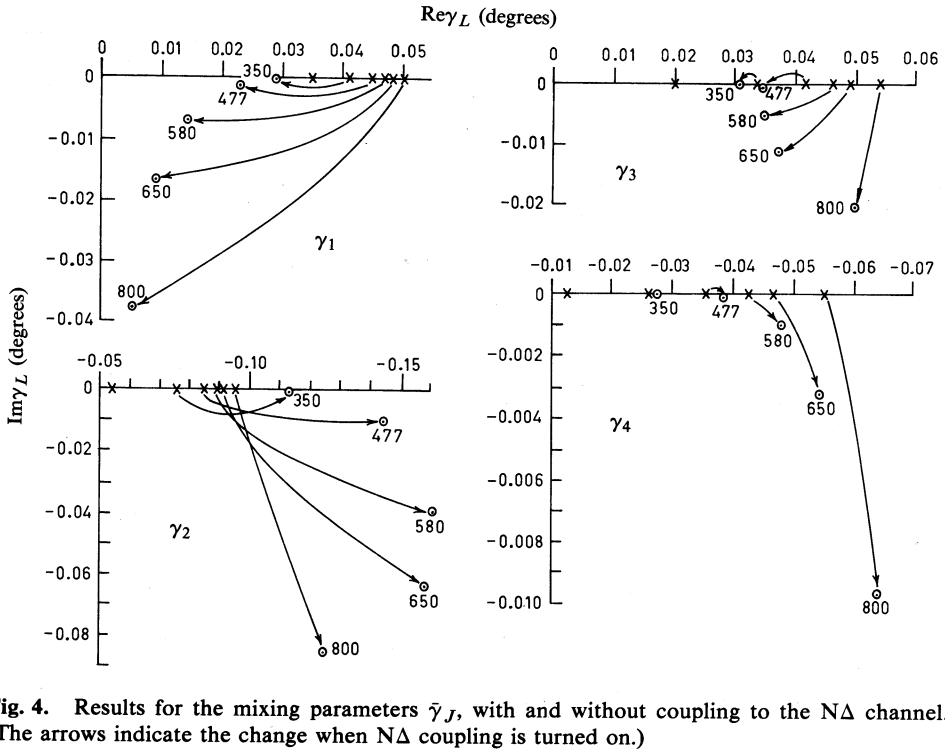

Fig. 4. Results for the mixing parameters $\bar{\gamma}_J$, with and without coupling to the NΔ channel. (The arrows indicate the change when NΔ coupling is turned on.)

where NΔ channel coupling is ignored. (The small difference arises because of the change in cut-off parameter $\Lambda_{NN\pi}$ from 600 to 700 MeV here.) Clearly both $\eta\pi^0$ mixing and Δ-mass differences appear to make a significant contribution.

The caution to which we now turn is associated with the fact that by including only the box diagrams shown in Fig. 1 we undoubtedly overestimate the isovector TPE force. Crossed box diagrams, which do not contribute any inelasticity at the energies studied here, are nevertheless known to cancel much of the isovector part of the boxes. Since it is the isovector force which is relevant for CSB we are certainly over-estimating the effect of the NΔ channel coupling. Clearly it is important to extend the present work to include crossed boxes and this is underway. Nevertheless, it is a long calculation and it seems worth while to us to show our preliminary estimate of the true effect in the following simple way.

In Fig. 4 we show the effect of channel coupling on the mixing parameters $\bar{\gamma}_J$, for J from 1 to 4. Following our discussion above we expect that the most reliable feature of our calculation is the imaginary part which each $\bar{\gamma}_J$ acquires. The shift in the real part is overestimated. We can show the effect of the imaginary parts by artificially setting them to zero. The dotted lines in Fig. 2 show the result of this experiment. The difference between the dotted and dashed curves is therefore the effect of the $\bar{\gamma}_J$ acquiring imaginary parts—an undeniable consequence of channel coupling. Clearly this effect is very small at 477 MeV, but grows rapidly until at 800 MeV it dominates ΔA near crossover.

4. Conclusions

In summary we have presented evidence that the effect of NΔ channel coupling on CSB in the np interaction rapidly becomes important above 500 MeV. There is clearly a need for more refined theoretical work, but already the case for beginning experimental tests in this energy region is persuasive.

Acknowledgments

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