Charge symmetry breaking in pion production

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Chiral effective field theory predicts a charge symmetry violating (CSB) amplitude for pion-nucleon scattering. This mechanism provides a very large contribution also to the CSB forward-backward asymmetry in the angular distribution of the reaction \( pn \rightarrow d\pi^0 \). This contribution was so large that it had a potential to cause a large effect also in CSB elastic \( NN \) scattering and to disturb its present understanding. However, it can be seen that, contrary to pion production, in this case the \( ud \)-quark mass difference and electromagnetic contribution to the \( np \)-mass difference tend to cancel causing the total effect in the effective range parameters \( \Delta a = a_{pp} - a_{nn} \) and \( \Delta r_0 = r_{0,pp} - r_{0,nn} \) to be relatively small. In the lowest order and within the static approximation for the nucleons CSB pion-nucleon rescattering does not influence \( np \) scattering.

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1. Introduction

Charge symmetry is a special case of the general flavour symmetry of QCD, which at its simplest distinguishes the proton and the neutron (or \( u \) and \( d \) quarks). It is, of course, trivially broken by the electromagnetic interaction, notably the Coulomb force in comparisons of the \( pp \) and \( nn \) systems and by the magnetic interaction in the \( np \) system. Other well known sources are the \( np \) mass difference and \( \eta \pi^- \)- as well as \( \rho \omega \)-meson mixing. These in turn may be related to the up- and down-quark mass difference - the microscopic flavour symmetry breaking in QCD. One might consider remarkable the fact that, although the relative quark mass difference is large (\( \geq 10\% \)), the symmetry breaking at the observable hadron level is two orders of magnitude smaller.

In the mirror system \( pp \) vs. \( nn \) CSB has been studied for many decades [1], while its appearance in the \( np \) system was first seen only a decade ago [2].

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as the difference $\Delta A = A_n - A_p$ of elastic analyzing powers. Different CSB observables have been seen in calculations to be sensitive to different combinations of sources. For example, in $np$ scattering above 300 MeV the $np$ mass difference in OPE dominates, while at and below $\approx 200$ MeV $\rho \omega$ meson mixing and the magnetic interaction become about equally important[3]. In contrast, the $pp$ vs. $nn$ difference is dominated by $\rho \omega$ meson mixing [1, 5, 4]. The CSB effects in the $np$ system change the total isospin of the two nucleons (class IV in the terminology of Ref. [6]), whereas in $pp$ and $nn$ the isospin must be conserved (class III).

2. CSB pion production

It is easily seen that in the reaction $np \rightarrow d\pi^0$ the isospin change $T = 0 \rightarrow 1$ implies a CSB asymmetry of the unpolarized cross section about 90° and vice versa. Namely, due to the generalized Pauli principle and conservation of the angular momentum and parity, with isospin one initial states for odd $l_\pi$ only singlet-even initial states are possible and for even $l_\pi$ only triplet-odd states. The presence of some isospin zero component in the initial state introduces opposite spin-parity assignments and the initial spin states will then have both parities involved. This minor asymmetry is being measured in an on-going experiment at TRIUMF [7].

Since class IV forces mentioned above change the isospin, as an initial state interaction they can quite naturally give rise to $d\pi^0$ final states even from initial $T = 0$ $np$ states. Further, although in a purely nucleonic basis $\eta \pi$ mixing force conserves the isospin (class III), it can cause a $T = 0 \Delta N$ admixture even in initial isospin zero states [8, 9, 10] and thus contribute to pion production from these states. In addition $\eta \pi$ mixing can contribute very explicitly in the final actual production vertex in the form of production first of an isoscalar $\eta$ meson which then transforms into a pion.

Of traditional CSB mechanisms in pion production $\eta \pi$ mixing is important and was seen to dominate at threshold [8], while the $np$ mass difference becomes more important at higher energies, where the two $\eta \pi$ mixing mechanisms described above tend to cancel [9].

Exploiting the fact that chiral symmetry gives predictions for effects arising from the small but explicit breaking of this symmetry generated by the quark masses, Ref. [11] employed a CSB effective Lagrangian based on chiral symmetry and including the $u$ and $d$ quark mass differences

$$L_{qm}^{(1)} = \frac{\delta m_N}{2} \left( N^\dagger \tau_0 N - \frac{2}{D F_\pi} N^\dagger \pi_0 \pi \cdot \tau N \right)$$

(1)

to describe pion-nucleon s-wave rescattering in $np \rightarrow d\pi^0$. This rescattering dominates isospin conserving production at threshold. Here $\tau$ represents the
Fig. 1. Isospin breaking pion-nucleon rescattering mechanisms in \( np \to d\pi^0 \) (a) and in \( NN \) elastic scattering (b and c).

Pauli matrices in isospin space, \( F_\pi = 186 \text{ MeV} \) is the pion decay constant, and \( D = 1 + \pi^2/F_\pi^2 \), though for simplicity \( D = 1 \) was used. It is important to note that the pion-nucleon interaction in the second term is linked by chiral symmetry to the first term, which in turn is directly related to the neutron-proton mass difference giving \( m_n - m_p = \delta m_N + \bar{\delta} m_N \). Here \( \bar{\delta} m_N \) is an electromagnetic "hard photon" exchange contribution to the neutron-proton mass difference also related to the isospin violating pion-nucleon interaction in the effective Lagrangian

\[
\mathcal{L}^{(-1)}_{hp} = \frac{\bar{\delta} m_N}{2} \left( N^\dagger \tau_0 N + \frac{2}{DF_\pi^2} N^\dagger (\pi_0 \pi \cdot \tau - \pi^2 \tau_0) N \right). \tag{2}
\]

This CSB rescattering mechanism is presented in Fig. 1a.

Above, the quark mass difference is by no means small as compared with their sum but rather \( m_d - m_u \equiv \varepsilon (m_d + m_u) \) with \( \varepsilon \sim 1/3 \), although the individual parameters \( \delta m_N \) and \( \bar{\delta} m_N \) are not completely uniquely determined and remain model dependent. Their values have reasonable ranges 2–3 MeV and (–0.5)–(–1.5) MeV, respectively.

At the TRIUMF experiment energy 279.5 MeV the integrated forward-backward asymmetry

\[
A_{fb} = \frac{\int_0^{\pi/2} d\Omega \left[ \sigma(\theta) - \sigma(\pi - \theta) \right]}{\int_0^{\pi} d\Omega \sigma(\theta)}.
\]  

(3)

was obtained in Ref. [11] in terms of the above mass differences as

\[
A_{fb} \simeq \left( -28 + \frac{24}{\text{MeV}} (\delta m_N - \bar{\delta} m_N/2) \right) \times 10^{-4}, \tag{4}
\]
where the conventional meson contributions in the first term have been taken from Ref. [8]. Due to the dominance of the $\eta\pi$ mixing, the uncertainties in its strength directly scale that term. Apart from minor pionic effects due to the $np$ mass difference, it is proportional to $G\eta(\pi|H|\eta)$. The values $C^2_{\eta}/4\pi = 3.68$ and $\langle \pi|H|\eta \rangle - 5900$ MeV$^2$ have been used for this result. (In addition, the analogous effect from $\eta'$ with the same coupling and the mixing matrix element $-5500$ MeV$^2$ was included [8].)

Since in Eq. (4) $\delta m_N$ and $\delta m_N^\ast$ add constructively, the latter term arising from the new effective Lagrangian easily dominates the total $A_{f_0}$ making it change sign. With the given first term, the total $A_{f_0}$ would vary in the range $0.3$–$0.6\%$. It is unlikely that the first term is an overestimate, so the range might rather be even more positive. With the anticipated experimental resolution of $0.12\%$ [7] this is a significant result. If the uncertainties in the $\eta\pi$ mechanisms (notably the $\eta NN$ coupling constant) can be solved, CSB pion production could set constraints also on $\delta m_N$ and $\delta m_N^\ast$.

3. Effect in elastic $NN$ scattering

Since the new effective CSB interaction gave such a large contribution in pion production, one is prone to worry how much this $\pi N$ rescattering might contribute to elastic $NN$ scattering possibly breaking the consensus there. In Ref. [12] the CSB $NN$ two-pion exchange interaction depicted in Fig. 1b was shown in lowest order (in the static approximation for baryons) to be of the form of class III

$$V_N(q) = \frac{\delta m_N + 2\delta m_N^\ast f^2}{F^2} \frac{f^2}{\mu^2} \int \frac{d^3k}{(2\pi)^3} \frac{(k^2 - q^2/4)(\tau_1 + \tau_2)}{[\mu^2 + (k + q/2)^2][\mu^2 + (k - q/2)^2]},$$

where $f^2/4\pi = 0.076$ is the pion-nucleon coupling constant and $\mu$ the pion mass. A similar expression resulted for exchanges involving an intermediate $\Delta(1232)$ isobar (Fig. 1c).

Contrary to pion production, in this case, although the integrals and parameters are rather large, the two mass differences cancel to a large extent leaving only rather small contributions to the difference between $nn$ and $pp$ scattering. To see this, one need only compare the range of the factor $\delta m_N + 2\delta m_N^\ast [+0.8\,\text{--\,}\,-0.2\,\text{MeV}]$ with the range of $\delta m_N - \delta m_N/2$ [2.2--3.4 MeV]. Correspondingly, the contributions to the scattering length and effective range differences $\Delta a = a_{pp} - a_{nn}$ and $\Delta r_0 = r_{0,pp} - r_{0,nn}$ vary between $0.17$ fm and $-0.05$ fm, and $0.003$ and $-0.001$ fm, respectively. Also the contribution from this source to the $^3\text{H}^\ast - ^3\text{He}$ binding energy difference is expected to be small.
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