12 pages

TRI-PP-89-4
Feb 1989

A new source for parity violating nuclear force

M.J. Iqbal and J.A. Niskanen[1]
TRIUMF, 4004 Wesbrook Mall, Vancouver, B.C., Canada V6T 2A3

Abstract

We propose a mechanism for parity violation in the two nucleon meson-exchange interaction by way of the mixing of mesons of opposite parities. This mixing arises from parity violating $W^{\pm}$ and Z exchange between the $q\bar{q}$ pair in the meson. Numerically its effect turns out to be as important as vector meson exchange with a weak meson-nucleon vertex. The calculation is performed using both the standard Born approximation adding the amplitude phases by Watson's theorem and also using the exact correlated two-nucleon wave functions. The effect of correlations and form factors is found to be crucially important at intermediate energies.

(submitted to Physical Review Letter)

[1]On leave from Department of Theoretical Physics, University of Helsinki.

Ca9109979

Studies of parity violating nuclear forces probe the flavour conserving part of weak hadronic interaction. So far such studies have concentrated on effects in nuclei. This is because in some cases parity mixed energy levels can be very near to each other (e.g. 0^-(1081 keV) and 0^+(1042 keV) levels in ^{18}F) thereby enhancing the mixing to a measurable level.[1] However, the drawback of this approach is the complications and consequent ambiguities due to nuclear structure calculations in the theoretical interpretation. Clearly, from the theoretical point of view, a two-body situation would be preferable. At the quark level even this is complicated enough. With the advent of meson factories with intense primary proton beams, searches for parity violation in two-nucleon scattering have become feasible at low and intermediate energies. A few such studies have already been performed at SIN[2] for $E_p = 45$ MeV and at Los Alamos[3,4] for $E_p = 15$ MeV and 800 MeV, and other experiments are at the planning stage.[5] These experiments measure the simplest parity violating observable, the average longitudinal analyzing power $\bar{A}_L$ (or $\bar{A}_z$) in polarized proton scattering off an unpolarized proton target. There appears, then, to be a need for theoretical work on parity nonconserving (PNC) nuclear forces.

Considerable work on PNC forces has indeed been done, see e.g., the review of Adelberger and Haxton.[1] After pioneering work by Henley and collaborators at the meson exchange level[7] the most extensive theoretical quark level treatment is that of Desplanques, Donoghue and Holstein (DDH)[6] , which serves as a starting point and measure stick for many other works. They incorporate three different PNC diagrams at the baryon-meson vertex. Shortly, these include an intermediate boson exchange between the meson and baryon, between two quarks and the self energy type contribution for a quark. DDH list 'best values' and 'reasonable ranges' for the strengths of various components of ρ and ω (and charged π) meson exchanges. These values are used e.g., by Oka to calculate the $\bar{A}_z$ asymmetry in pp scattering .[8] However, as in ref. 1 these results still need some scaling to fit the data.

In this letter we introduce a new mechanism for parity violation, meson mixing due to the weak force. The exchange of $W^{\pm}$ and Z^0 between the quark and antiquark as depicted in fig. 1 can cause a mixing of mesons of opposite parities, the mixing of the ρ and a_1 or ω and f_1 mesons. The physics is very similar to that of isospin mixing of π and η or ρ and ω mesons due to the electromagnetic interaction of the quarks and the u and d quark mass difference.[9] Once parity has been mixed at the meson level, PNC goes over to the NN interaction in the perfectly standard meson exchange picture with strong meson-nucleon couplings. One should note that although the positive parity mesons are heavy, they act much like a form factor on the ρ or ω exchange, allowing the latter to determine the overall range of the interaction. *A priori* there is no reason why this mechanism should be any less important than the weak interaction at the meson-baryon vertex considered e.g. by DDH.[6] Also parity violating components in the internal nucleon wavefunctions have been proposed as a way to explain large PNC at high energies .[10]

To derive parity mixing in mesons one has to consider the interference term of the γ^μ and $\gamma^\mu\gamma^5$ operators in the $W^{\pm}$ or Z exchange between a quark and an antiquark (fig. 1a) and in the corresponding annihilation diagram (fig. 1b). The approximation of zero Weinberg angle $\theta_W = 0$ and omitting the gauge term in the propagator and terms of order p^3/m_q^3 or higher leads to the nonrelativistic PNC operator

$$\theta = -\frac{g^2}{4M_W^2}\frac{(\vec{p}\,' + \vec{p})}{2m_q}\cdot\vec{S}\left[\frac{9}{2} + \frac{1}{2}\,\vec{\tau}_1\cdot\vec{\tau}_2\right] .$$

Here the isospin operators are to be interpreted as acting on the *actual* physical isospin, *not* on the *absence* of an isospin. A nonzero Weinberg angle would break the isospin symmetry. In pp scattering, however, this would not cause any essential changes. Also the present nonrelativistic approximation is purely for convenience and clarity and will be further studied in a forthcoming work.

The operator θ changes the parity but *not the spin*. Consequently, the pseudoscalar pion cannot mix with the scalar a_0. For neutral mesons this can be considered as an example of the Barton's theorem,[12] which by CP conservation forbids a parity violating neutral $J = 0$ meson exchange in the NN system. In fact, the CP symmetry does prevent the mixing of π^0 with a_0^0. However, the present result is more general. The spin structure of θ excludes also the mixing of $\pi^\pm$ and $a_0^\pm$, for which the charge conjugation parity is not well defined. Therefore we are led to study only vector meson mixing with an axial vector.

For harmonic oscillator wave functions the matrix element becomes

$$\left\langle {}^3P_1|\theta|{}^3S_1\right\rangle = \frac{\alpha^2}{\pi^{3/2}}\frac{\sqrt{2}\,G_F}{m_q} \times \begin{cases} 3 & T=0 \\ 5 & T=1 \end{cases} .$$

Here the weak coupling constant is[11] $G_F = \sqrt{2}\,g^2/8M_W^2 = 1.17\times10^{-5}$ GeV^{-2}, and the parameter $\alpha = \frac{3}{4}\left\langle r^2\right\rangle_{ch}^{-1} \approx 1.7$ fm^{-2} to fit approximately the meson radius 0.66 fm. (We use the pion charge RMS radius from ref. 13.) The quark mass is taken to be 350 MeV. This gives the mixing matrix elements the values

$$\langle a_1|\theta|\rho\rangle = 0.38 \text{ MeV}^2\,, \quad \langle f_1|\theta|\omega\rangle = 0.23 \text{ MeV}^2\,,$$

where a factor of $2\sqrt{m_\rho m_{a_1}}$ $\left(2\sqrt{m_\omega m_{f_1}}\right)$ has been added to the nonrelativistic $q\bar{q}$ result to account for the relativistic normalization of the meson fields. These are about a factor 10^{-4} smaller than those for isospin breaking $\pi\eta$ and $\rho\omega$ mixings,[9] but as weak interaction induced parity violation they are quite considerable. One should note, however, that there may be strong sensitivity on the particular model chosen for the meson. Presently we shall go ahead with the simple oscillator model to obtain just the first estimate of this new PV mechanism and leave the model dependence for further study in the future.

Now it is easy to derive the NN interaction due to ρa_1 exchange. Using the meson-nucleon couplings

$$\mathcal{L}_{\rho NN} = i\overline{\psi}\left(g_\rho\gamma^\mu + \frac{if_\rho}{2M}\,\sigma^{\mu\nu}\,q_\nu\right)\vec{\rho}_\mu\cdot\vec{\tau}\psi\ ,$$

and[14]

$$\mathcal{L}_{a_1 NN} = \lambda/2\,\overline{\psi}\,\gamma^\mu\gamma_5\,\vec{\tau}\cdot\vec{A}_\mu\psi\ ,$$

where the a_1 coupling is related to the πNN coupling by the chiral symmetry $\lambda/2m_{a_1} = f_{\pi NN}/m_\pi$, one obtains in momentum space

$$V_{\rho a_1} = \frac{\lambda}{2}\,\frac{\langle a_1|\theta|\rho\rangle}{m_{a_1}^2 - m_\rho^2}\,\frac{1}{M}\,\left[(g_\rho + f_\rho)i(\vec{p}\,' - \vec{p})\cdot(\vec{\sigma}_1\times\vec{\sigma}_2) + g_\rho(\vec{p}\,' + \vec{p})\cdot(\vec{\sigma}_1 - \vec{\sigma}_2)\right]\times$$
$$\times\left(\frac{1}{\vec{q}^{\,2} + m_\rho^2} - \frac{1}{\vec{q}^{\,2} + m_{a_1}^2}\right)\vec{\tau}_1\cdot\vec{\tau}_2\ .$$

Here M is the nucleon mass, the ρ coupling constants are[15] $g_\rho^2/4\pi = 0.55$ and $f_\rho/g_\rho = 6$, and $f_{\pi NN}^2/4\pi = 0.08$ gives $\lambda/2 = 9$. Mixing of the ω and f_1 mesons is similar except for the isospin dependence. In this case the f_1 coupling to nucleons is more uncertain than for a_1, where chiral symmetry arguments can be used to relate the a_1 coupling to that of the pion.[14] Even the latter has some uncertainty since local chiral symmetry is broken. For the moment we shall omit the ωf_1 mixing, since it is similar to the ρa_1 mixing and acts to scale the effect.

After Fourier transformation, except for the a_1 term, $V_{\rho a_1}$ is exactly of the same form as the standard isoscalar part of PNC ρ exchange (see eq. (4) of ref. 1) with the effective strength parameter

$$F_0(eff) = g_\rho \, \frac{\lambda}{2} \, \frac{\langle a_1|\theta|\rho\rangle}{m_{a_1}^2 - m_\rho^2} \, .$$

The above oscillator model gives an estimate $F_0(eff) \approx 8.9 \times 10^{-6}$. Even allowing for the fact that the partial cancellation of the ρ and a_1 terms in $V_{\rho a_1}$ reduces the interaction by a factor of about $\frac{1}{3}$, it is still stronger than the weak ρ exchange using the "best value" of DDH[1] $F_0 = 1.59 \times 10^{-6}$. Therefore, there is all reason to believe that meson mixing is an important contribution to parity violation, albeit strongly dependent on the model of the mesons. The use of a linear confining potential presumably decreases the mixing matrix element. Making the meson smaller, on the other hand, increases mixing as $\langle r^2\rangle_{ch}^{-2}$, as well as does the attractive one gluon exchange Coulomb term at short distances of the quarks. Coupling to meson decay channels tends to decrease the $q\bar{q}$ wave function at short distances, decreasing also the mixing matrix element. Finally, in constructing the PNC NN potential one should incorporate the finite size and composite structure of the hadrons to nucleon-meson vertices. This gives rise to form factors which have been ignored in earlier calculations. The use of reasonable cut-offs weakens the potential and decreases the observable $\bar{A}_L$ by about a factor of $\frac{1}{2}$ as compared with the case of point hadrons. In addition to these possible or necessary modifications in the interaction itself, the correlation of the two nucleons at short distances has an effect of $\frac{1}{6}$ to $\frac{1}{2}$ on $\bar{A}_L$. This is also ignored in most earlier works, where only the asymptotic phase shift effect was incorporated by Watson's theorem into Born approximation calculations.

Figure 2 shows the contribution to the parity violating observable $\bar{A}_L$ arising from ρa_1 mixing in the above described model including just the dominant ${}^3S_0 - {}^3P_0$ partial waves. The solid curve shows the Born approximation results without any meson-nucleon form factors, whereas in the dashed curve a dipole form-factor with $\Lambda_\rho = 1400$ MeV and $\Lambda_{a_1} = 2000$ MeV as in the Bonn potential[16] has been included at each vertex. The phase shifts are taken from the SAID analysis of Arndt *et al.*.[17] The energy dependence is very similar to standard vector meson exchange results with a weak coupling vertex. This is not surprising, because the PNC two nucleon potentials are also similar and because the main features of $\bar{A}_L$ are determined by the strong phases. If the form factors are ignored, then also the magnitude is comparable to that obtained by Oka using vector meson exchange.[8] The boxes show the effect of the correlation in the wave functions calculated using the Reid soft core potential.[18] It is seen that omitting either the form factors or the correlations is apparently a bad approximation and overestimates the effect by nearly an order of magnitude as compared with exact calculations. It is particularly unexpected that correlations appear more important at energies above 500 MeV. This must be due to the short range of the PNC interaction stressing the short range behaviour of the wave functions. This energy dependence was checked by gradually weakening the distorting strong interaction at 500 MeV and showing that the result converged to the Born approximation.

Figure 3 shows the experimental results and slight effect of $^3P_2 -^1 D_2$ mixing amplitude. In this calculation of both mixing amplitudes the form factors were included, but no correlations. Apparently the use of only $^1S_0 - ^3P_0$ mixing is relatively quite a reasonable approximation, if solely nucleonic states are included. However, in absolute terms the $^3P_2 - ^1D_2$ contribution is not so small. At the energy where the $J = 0$ term passes through zero (in our calculation 230 MeV), the effect of the $^3P_2 - ^1D_2$ mixing in $\bar{A}_L$ is about 0.6×10^{-7}. One aim of the planned TRIUMF experiment[5] at this energy is to set constraints on standard model predictions for weak vector meson couplings specific for $J \neq 0$ amplitudes. The present result should influence on the conclusions to be drawn from the experiment. The $^3F_2 - ^1D_2$ mixing was found to be negligible. We still note that an effect which can also make the $J = 2$ states more important is a possibility of admixing a virtual $^5S(N\Delta)$ component with the $^1D_2$ nucleon state in the two pion exchange contribution.[19]

In summary, parity violating meson mixing seems to be an important part of the PNC nuclear force. Our present results based upon the oscillator model for mesons suggest that this contribution alone is about as large as modern calculations[20] indicate to arise from the standard vector meson exchanges, and would be enough to produce the low energy experimental data. When it is combined with ρ and ω exchanges, there might appear to be some excess as compared with experiment. However, the addition of meson mixing even at its present level to the vector meson exchanges, does not necessarily contradict experiment, since PNC two pion exchange involving an intermediate $N\Delta$ state seems to be of the opposite sign to these effects, partly cancelling them.[19] Quite obviously the new mechanisms should have a profound effect on attempts, such as refs. 5 and 21, to set direct experimental or phenomenological constraints on the weak ρNN and ωNN couplings. Of course, to get a more reliable result, one needs a more sophisticated model for the mesons. On the other hand, because of the sensitivity of PNC interaction on the meson wave function, if we could put reasonable limits on other uncertainties (e.g. form factors), PNC measurements might be used as a probe of the meson structure. It would be of particular interest to see whether PNC meson mixing could be seen directly in meson decays.

Acknowledgements

We thank P.G. Blunden for useful discussions and W. T. H. van Oers for a critical reading of the manuscript.

References

[1]E.G. Adelberger and W.C. Haxton, Ann. Rev. Nucl. Part. Sci. **35**, 501 (1985).

[2]R. Balzer *et al.*, Phys. Rev. C **30**, 1409 (1984); S. Kistryn *et al.*, Phys. Rev. Lett. **58**, 1616 (1987).

[3]J.M. Potter *et al.*, Phys. Rev. Lett. **33**, 1307 (1974); D. Nagle *et al.*, Proc. 3rd Int. Symp. on High Energy Physics with Polarized Beams and Polarized Targets, Argonne 1978, AIP Conf. Proc. **51**, 224 (1979).

[4]R.W. Harper *et al.* Phys. Rev. D**31**, 1151 (1985); V. Yuan *et al.*, Phys. Rev. Lett. **57**, 1680 (1986).

[5]S.A. Page, J. Birchall and W.T.H. van Oers (Spokespersons), TRIUMF experimental proposal E497.

[6]B. Desplanques, J.F. Donoghue and B.R. Holstein, Ann. Phys. **124**, 449 (1980).

[7]V.R. Brown, E.M. Henley and F.R. Krejs, Phys. Rev. Lett. **30**, 770 (1973), Phys. Rev. C**9**, 935 (1974); E.M. Henley and F.R. Krejs, Phys. Rev. D**11**, 605 (1975).

[8]T. Oka, Prog. Theor.. Phys. **66**, 977 (1981).

[9]S.A. Coon and R.C. Barrett, Phys. Rev. C **36**, 2189 (1987); S.A. Coon, B.H.J. McKellar and M.D. Scadron, Phys. Rev. D **34**, 2784 (1986).

[10]G. Nardulli and G. Preparata, Phys. Lett. **137B**, 111 (1984); B. Desplanques and S. Noguera, Phys. Lett. **144B**, 255 (1984); T. Goldman and D. Preston, Phys. Lett. **168B**, 415 (1986).

[11]F. Halzen and A. Martin, Quarks and Leptons (Wiley, New York, 1984).

[12]G. Barton, Nuovo Cimento **19**, 512 (1961).

[13]E. B. Dally *et al.*, Phys. Rev. Lett. **48**, 375 (1982); S. R. Amendolia *et al.*, Phys. Lett. **138B**, 454 (1984).

[14]J.W. Durso, G.E. Brown and M. Saarela, Nucl. Phys. **A430**, 653 (1984).

[15]G. Höhler and E. Pietarinen, Nucl. Phys. **B95**, 210 (1975); W. Grein, Nucl. Phys. **B131**, 255 (1977).

[16]R. Machleidt, K. Holinde and Ch. Elster, Phys. Rep. **149**, 1 (1987).

[17]R.A. Arndt *et al.*, Phys. Rev. **D28**, 97 (1983).

[18]R.V. Reid, Ann. Phys. **50**, 411 (1968).

[19]R.R. Silbar, W.M. Kloet, L.S. Kisslinger and J. Dubach, Contr. to Spin and High Energy Physics Conference, Minneapolis, (1988).

[20]D.E. Driscoll and G.A. Miller, Univ. of Washington preprint (1988).

[21]F. Nessi-Tenaldi and M. Simonius, Phys. Lett. **215B**, 159 (1988).

Figure captions

1. The mechanism for PNC in mesons: intermediate vector boson exchange as a direct (a) and exchange (or annihilation) diagram (b).

2. The effect of form factors and pp wavefunction correlations by the Reid soft core potential on the average longitudinal analyzing power $\tilde{A}_L$ including only ${}^1S_0 - {}^3P_0$ mixing.

3. The effect of including also the ${}^3P_2 - {}^1D_2$ partial waves. The boxes show the available experimental data.

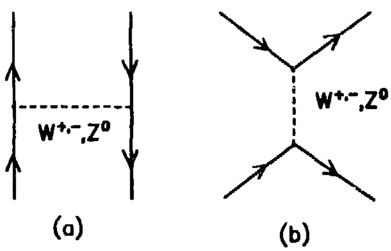

Fig. 1

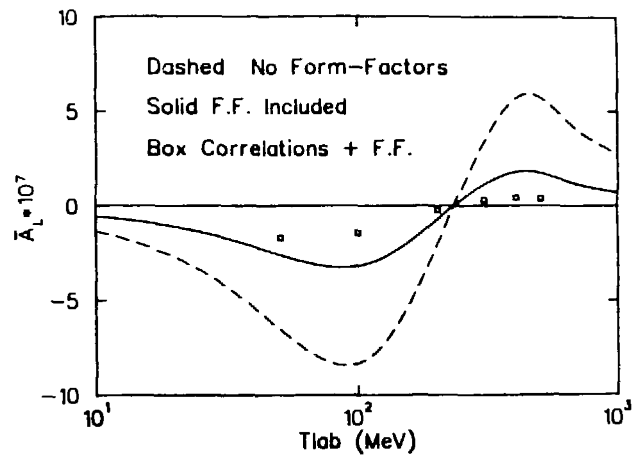

Fig. 2.

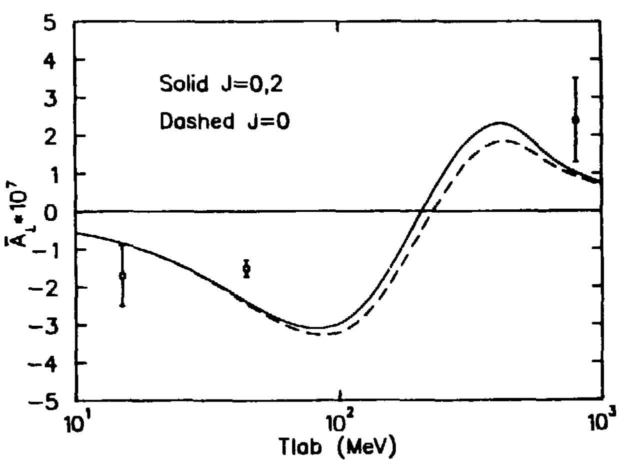

Fig. 3.