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Charge dependence and charge asymmetry of nuclear forces in chiral quark cluster models

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Abstract

We discuss charge-dependent effects on nucleon–nucleon scattering lengths in chiral quark cluster models. We find that, as in meson-exchange models, the pion-mass splitting can account for about 60% of the experimental difference between proton–proton and proton–neutron scattering lengths. Adding QED–QCD interference effects both the charge independence and charge symmetry breaking are reasonably understood. © 1999 Published by Elsevier Science B.V. All rights reserved.

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The understanding of the difference between proton–proton (pp), proton–neutron (pn) and neutron–neutron (nn) interaction endures as one of the intriguing and partially unsolved problems on the description of nuclear forces [1,2]. To this respect, the NN scattering length in the $^1S_0$ state plays a special role because it is extremely sensitive to small differences in the strength of the force. The values of proton–proton, neutron–neutron and proton–neutron scattering lengths ($a_{\rm pp}$, $a_{\rm nn}$ and $a_{\rm pn}$, respectively), after Coulomb effects are removed, indicate that the pn force is, in average, slightly more attractive than nn and pp forces, whereas the nn interaction is more attractive than the pp interaction. Experimental values for the different NN scattering lengths in the $^1S_0$ state are listed in Table 1. From these data one can define the charge symmetry breaking (CSB) combination,

$$\Delta a_{\rm CSB} = a_{\rm pp} - a_{\rm nn} = 1.5 \pm 0.5 \ \ {\rm fm}\ , \quad (1)$$

which shows that this symmetry is slightly broken in nature. However, the charge independence breaking (CIB) combination,

$$\Delta a_{\rm CIB} = \tfrac{1}{2}(a_{\rm pp} + a_{\rm nn}) - a_{\rm pn} = 5.7 \pm 0.5 \ \ {\rm fm}\ , \quad (2)$$

shows a sizeable value which clearly demonstrates that nuclear interactions are charge dependent.

There has been a considerable amount of theoretical activity to reproduce and understand these numbers [3–13]. Most of the theoretical calculations try to explain the data using meson-exchange models [3–9]. This approach incorporates basically isospin breaking through the charged and neutral pion-mass difference, the proton–neutron mass difference, the ρ^0–ω electromagnetic mixing amplitude, and the electromagnetic corrections. Whereas part of the CIB has been explained by means of the mass difference between neutral and charged pions, proton–neutron mass difference and ρ^0–ω mixing have been used to account for CSB effects.

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Table 1
Experimental values of nucleon–nucleon $^1S_0$ scattering length. The values given for pp and nn refer to the nuclear part of the interaction. Electromagnetic effects have been removed from the experimental values, which is model dependent. The uncertainties quoted for a_{pp} and a_{nn} are mainly due to this model dependence. Data are taken from Ref. [1]

$^1S_0$ scattering length	Exp. value (fm)
a_{pp}	-17.3 ± 0.4
a_{nn}	-18.8 ± 0.3
a_{pn}	-23.75 ± 0.01

The role played by the neutral and charged pion mass difference on CIB has been recently investigated within the framework of the Bonn potential for the NN interaction, which is entirely based on meson exchanges. Cheung and Machleidt and Li and Machleidt [4] find in this model that the pion-mass difference can account for about 80% of the experimental discrepancy between pp and pn scattering lengths. 70% of this number comes from OPE, whereas the remaining 30% is due to 3π and 4π exchanges implemented as $\pi\sigma + \pi\omega$ exchanges. The contribution of 2π diagrams almost cancels with the $\pi\rho$ exchange. Similar results were also previously obtained by Ericson and Miller [3]. These authors also considered a second contribution to CIB coming from the electromagnetic loop corrections to the one-pion exchange, generating a simultaneous $\pi\gamma$-exchange force between nucleons. Because the photon is massless, the $\pi\gamma$-force has a nominal OPE range. This correction has recently been evaluated by Friar and Coon [5] and van Kolck et al. [6] in the framework of chiral perturbation theory. Although in Ref. [5], working with a subset of Feynman diagrams for which the photon (in the Coulomb gauge) traverses from one nucleon to another, a negative contribution of roughly 3% to Δa_{CIB} was obtained, the full calculation of Ref. [6] demonstrated that this contribution is negligible. Other possible contributions to CIB, as for example charge dependence of the πNN coupling constant or isobar contributions to the $\pi\gamma$-exchange force have been also found to give negligible contributions [3,5]. Therefore, at least 15% of Δa_{CIB} remains unexplained by meson-exchange models.

The situation is different for CSB. As mentioned before, two mechanisms have been invoked in meson-exchange models to account for CSB. In the first one [7,8], CSB is mostly attributed to the proton–neutron mass difference which appears in the two-pion exchange graphs involving one nucleon and one delta. This mass difference affects the kinetic energy of the nucleon and besides, it also influences all meson-exchange diagrams, mainly through the propagation of nucleon intermediate states with the correct mass in 2π-exchange diagrams. A different mechanism [9] explains CSB through the contribution to the NN force of the electromagnetic mixing amplitude between the isoscalar ω meson and the neutral member of the isovector ρ meson. There has been discussion about the role of the contributions mentioned above. Traditionally, it was believed that the ρ^0–ω mixing explained essentially all CSB in nuclear forces. However, different theoretical investigations [14,15] found that ρ^0–ω exchange may have a substantial q^2 dependence, such as to cause this contribution to nearly vanish in NN. However, the issue of the q^2 dependence of this mixing amplitude is by no means settled, and therefore from the point of view of meson-exchange models seems to be premature to draw any definitive conclusion.

From a more fundamental point of view one would expect that the source of Δa_{CIB} and Δa_{CSB} could be ultimately traced to CIB and CSB in Quantum Chromodynamics. The traditional quark-model approach incorporates only two sources of isospin breaking, namely up–down quark mass difference and the Coulomb interaction arising from the antisymmetrization of the quark wave function.

Chemtob and Yang [10] first gave a detailed description of the explicit quark contributions to the isospin-violating part of the nucleon–nucleon interaction. They used a hybrid non-relativistic quark-potential model including the one-gluon and one-photon exchange between quarks. These two potentials are supplemented with a local intercluster interaction coming from the folding of a π and σ two-body quark interaction, omitting the tensor and contact δ forces. They concluded that the up–down quark-mass difference produces $\Delta a_{CSB} \sim 2$–3.5 fm and Δa_{CIB} compatible with zero. Later on, Bräuer, Faessler and Henley [11] shown in a model based on an one-gluon exchange (OGE) and with a different prescription for the folded π and σ potentials that the quark-mass difference only contributes to Δa_{CSB}

as 0.46 fm because of a close cancellation between the contributions from the kinetic energy and the color-magnetic interaction. They found a small contribution to Δa_{CIB} (0.12 fm). Calculations of Refs. [10] and [11] were reviewed by Wang et al. [12] confirming that the quark-mass difference contribution to Δa_{CIB} is small but the contribution to Δa_{CSB} is model dependent.

Some years ago, Stephenson, Maltman, and Goldman (SMG) [16–18] proposed another source of isospin violation at the quark level due to the interference of QED and QCD terms. These interference effects are equivalent to the electromagnetic corrections to the one-pion exchange potential [5,6] but now refers to the one-gluon exchange interaction. SMG demonstrated that these electromagnetic corrections to one-gluon exchange diagrams give a significant contribution to the baryon isomultiplet mass splitting [17,18] and to the binding energy difference between ^{3}He and ^{3}H [16,18]. The QED–QCD interference effects contribute both to Δa_{CIB} and Δa_{CSB}. Wang et al. [13] have calculated both quantities using the Resonating Group Method (RGM) with a non-relativistic hamiltonian including one-gluon exchange interaction and up–down mass difference besides the interference terms. They found significant contributions of these last terms, but their results vary from 1.50 to 3.45 fm for Δa_{CSB}, and from from -1.52 to 7.33 fm for Δa_{CIB}, depending on the parameters used.

In order to establish the validity of the different calculations it is important to note that the change of the scattering length depends on the 'starting value' to which the effect is added [3]. Therefore all the reliable calculations should be able to reproduce the experimental *NN* phase shifts. However, most of the calculations done at the quark level introduce the intermediate and long-range part of the *NN* interaction in a phenomenological way and therefore, although including mechanisms which produce charge dependence of nuclear forces, one cannot fully trust on the size of the effects predicted.

In recent years, a chiral quark cluster model for the *NN* interaction that is able to reproduce the experimental data with a high quality has been developed by the Salamanca-Tübingen groups. This model has been widely described in the literature [19–21]. Our purpose in this work is to study charge-dependent effects based on the first quark potential model compatible with scattering and bound state data for the *NN* system.

We will summarize here only those facts which are relevant for the issue under consideration. The Salamanca-Tübingen potential incorporates, as a consequence of chiral symmetry breaking, a pseudoscalar and a scalar exchange between quarks coming from the lagrangian,

$$L_{ch} = g_{ch} F(q^2) \bar{\psi} (\sigma + i\gamma_5 \boldsymbol{\tau} \cdot \boldsymbol{\pi}) \psi , \qquad (3)$$

where $F(q^2)$ is a monopole form factor

$$F(q^2) = \left[\frac{\Lambda_\chi^2}{\Lambda_\chi^2 + q^2} \right]^{\frac{1}{2}} , \qquad (4)$$

Λ_χ determining the scale of chiral symmetry breaking and being bound between 1 GeV and 600 MeV [22]. The chiral coupling constant g_{ch} is chosen to reproduce the experimental πNN coupling constant. In this process the average value of $m_{\pi^\pm}$ and m_{π^0} masses is taken as scaling mass, avoiding in this way the creation of an artificial charge dependence.

From the above Lagrangian an one-pion exchange potential between quarks can be easily derived in the non-relativistic approximation,

$$V_{OPE}(q) = -\frac{g_{ch}^2}{4m_q^2} \frac{\Lambda_\chi^2}{\Lambda_\chi^2 + q^2} \frac{(\boldsymbol{\sigma_1} \cdot \boldsymbol{q})(\boldsymbol{\sigma_2} \cdot \boldsymbol{q})}{m_\pi^2 + q^2} \times (\boldsymbol{\tau_1} \cdot \boldsymbol{\tau_2}) . \qquad (5)$$

When the mass difference between charged and neutral pions is taken into account, V_{OPE} generates a charge-dependent one-pion exchange potential.

Using the range of values for Λ_χ given above, an estimation of the Δ–N mass difference due to the OPE interaction varies between 150 and 200 MeV. The rest of the mass difference, up to the experimental value, must have its origin on perturbative processes. This is taken into account through the well established one-gluon exchange potential [23]

$$V_{OGE}(q) = \alpha_s (\boldsymbol{\lambda_i} \cdot \boldsymbol{\lambda_j}) \times \left\{ \frac{\pi}{q^2} - \frac{\pi}{4m_q^2} \left[1 + \tfrac{2}{3} (\boldsymbol{\sigma_i} \cdot \boldsymbol{\sigma_j}) \right] + \frac{\pi}{4m_q^2} \frac{[\boldsymbol{q} \otimes \boldsymbol{q}]^{(2)} \cdot [\boldsymbol{\sigma_i} \otimes \boldsymbol{\sigma_j}]^{(2)}}{q^2} \right\} . \qquad (6)$$

Table 2
Quark model parameters

m_q(MeV)	313
b [a] (fm)	0.518
α_s	0.498
g^2_{ch}	6.661
m_σ(fm^{-1})	3.421
Λ_χ(fm^{-1})	4.300

[a] b is the parameter of the harmonic oscillator wave function used for each quark $\eta(x)=\left(\frac{1}{\pi b^2}\right)^{(3/4)} e^{-(x^2/2b^2)}$.

Although the direct-Coulomb effects are subtracted from the experimental scattering lengths, at the level of quarks there are still contributions coming from the simultaneous exchange of photons and quarks between the nucleons. The potential producing the quark-exchange Coulomb interaction is given by

$$V_\gamma(q) = 4\,\alpha\,Q_i Q_j \left\{ \frac{\pi}{q^2} - \frac{\pi}{4m_q^2}\left[1+\tfrac{2}{3}(\boldsymbol{\sigma_i}\cdot\boldsymbol{\sigma_j})\right]\right\}, \tag{7}$$

where Q_i is the charge operator of quark i.

Finally, we introduce the QED–QCD interference terms proposed by SMG [17] and obtained by Wang et al. [13] from a perturbative calculation where the vertex electromagnetic penguin, photon and gluon box and crossing diagrams are included,

$$V_I(q) = \pi\alpha_s\alpha(\boldsymbol{\lambda_i}\cdot\boldsymbol{\lambda_j}) \times \left\{ \frac{16(1-\log 2)}{4\pi}\frac{Q_iQ_j}{q^2} - \frac{12(1+\log 2)}{4\pi m_q^2} Q_iQ_j(\boldsymbol{\sigma_i}\cdot\boldsymbol{\sigma_j}) - \frac{\left(Q_i^2+Q_j^2\right)}{3\pi m_q^2}(\boldsymbol{\sigma_i}\cdot\boldsymbol{\sigma_j})\right\}, \tag{8}$$

In these potentials we do not distinguish between up and down constituent quark masses. Although this mass difference does not affect to charge dependence, it will contribute to charge asymmetry. This contribution will be discussed below.

Let us note at this point that the Salamanca–Tübingen chiral quark model does not contain any massive vector meson-exchange potentials (ρ, ω). The problem of unifying the quark-exchange and meson-exchange in the nuclear force and nuclear currents has been a matter of discussion [24]. It has been shown that the pseudoscalar (π) and scalar (σ) meson-exchange can be simply added to the quark-exchange terms without risk of double counting. However, the vector meson exchanges, which play an important role in meson models, need some care. In one boson exchange models, the ω meson provides most part of the short-range repulsion of the NN interaction. This task is taken over by the OGE combined with the antisymmetrization effects on the OPE in the chiral quark cluster model. Besides, the ρ meson reduces the strength of the tensor pionic interaction, the same effect is obtained from the quark-exchange terms of the one-pion exchange potential.

The phase shifts and scattering lengths for the $^1S_0$ partial wave have been calculated using a refined multichannel RGM calculation in momentum space [25]. The model parameters are those of Ref. [20], although a fine tuning has been performed to reproduce the exact value for the $^1S_0$ scattering length in presence of the QED–QCD interference terms. The parameters are shown in Table 2. For the pion masses we take the experimental values $m_{\pi^\pm}=$ 139.57 MeV and $m_{\pi^0}=134.97$ MeV. The calculation includes the tensor coupling $^1S_0(NN)$– $^5D_0(N\Delta)$ in order to reproduce the experimental phase shifts [20].

Let us first consider charge invariance breaking. Both, the pion-mass difference and the QED–QCD interference terms contribute to Δa_{CIB}. In Table 3 we show the different contributions to Δa_{CIB}, denot-

Table 3
CIB contributions to the $^1S_0$ scattering length, Δa_{CIB}. The numbers between parenthesis in the last two columns are calculated including the contribution of charge symmetry breaking

V^C_{OPE}	V^T_{OPE}	V^E_I	V^M_I	V_γ	a_{pn}(fm)	$\bar{a}_{pp(nn)}$ [a] (fm)	Δa_{CIB}(fm)
×	–	–	–	–	−21.559	−18.487	3.07
×	×	–	–	–	−21.807	−18.396	3.41
×	×	×	–	–	−22.085	−18.298	3.79
×	×	×	×	–	−23.451	−17.863	5.59
×	×	×	×	×	−23.749	−17.777	5.97
						(−17.807)	(5.94)

[a] $\bar{a}_{pp(nn)}=\frac{1}{2}(a_{pp}+a_{nn})$

Table 4
CSB contributions to the $^1S_0$ scattering length, Δa_{CSB}

V_I^E	V_I^M	V_γ	a_{pp} (fm)	a_{nn} (fm)	Δa_{CSB} (fm)
–	–	×	−17.649	−17.907	0.26
×	×	–	−17.195	−18.400	1.20
×	×	×	−17.075	−18.539	1.46

ing by the different entries the central (V_{OPE}^C) and the $^1S_0(NN)$– $^5D_0(N\Delta)$ tensor coupling (V_{OPE}^T) of the OPE potential, the spin-independent (V_I^E) and spin-dependent (V_I^M) parts of the QED–QCD interference terms, and the quark-exchange Coulomb effect (V_γ) [1]. The main contribution to Δa_{CIB} comes, as in meson-exchange models, from the central piece of the OPE potential. It represents, together with the one generated by the tensor part, almost 60 % of the experimental value. The contribution coming from the quark-exchange Coulomb interaction is small and represents less than 7 % of the experimental value. The QED–QCD interference terms give a sizeable contribution which, added with the former ones, is able to reproduce the experimental data.

The QED–QCD interference terms also generate charge symmetry breaking. As can be seen in Table 4, they give a sizeable contribution, much bigger than the effects of quark-exchange Coulomb interaction. Adding together these two terms, one obtains almost the correct value of the CSB correction to the scattering lengths. CSB influences CIB through the term $a_{pp}+a_{nn}$ incorporated into the definition of Δa_{CIB}. Such effect is given in the last two columns of Table 3 between parenthesis, representing a very small correction of 0.03 fm.

In the results quoted above the effects induced by the difference between the up and down constituent quark masses have not been considered. While the constituent mass is related to the scale of chiral symmetry breaking, the up–down constituent mass difference has been traditionally determined through the hadron isomultiplet splittings. As a consequence, constituent quark mass differences are in turn dependent on the assumptions of the model one is working with. Nevertheless, the influence of $\Delta m = m_d - m_u$ on Δa_{CSB} can be evaluated. Since the mass splitting of the up and down quarks is small, we can write

$$\frac{1}{m_i m_j} = \frac{1}{m^2}\left[1 + \frac{\Delta m}{2m}\left(\tau_i^z + \tau_j^z\right)\right], \tag{9}$$

where $m = 313$ MeV. This correction generates CSB on the kinetic energy, the OGE interaction (Eq. (6)), the OPE interaction (Eq. (5)), the quark-exchange Coulomb interaction (Eq. (7)), and the QED–QCD interference terms (Eq. (8)), being the last one negligible.

As in Ref. [10], there is a cancellation between the CSB induced by Δm on the kinetic energy and that induced on the OPE and OGE interactions. In our case, the cancellation is even more pronounced due to the effect of the tensor coupling with the NΔ channel which has the same sign as the kinetic energy correction. For values of Δm ranging from -5 MeV to 5 MeV, the total correction to CSB depends linearly on Δm and Δa_{CSB} can be expressed as $\Delta a_{CSB} = (1.46 + 0.07\Delta m)$ fm, when Δm is given in MeV. From this expression one obtains for Δa_{CSB} results between 1.39 fm and 1.74 fm for the interval of possible values of Δm deduced from the hadron isomultiplet splittings in Ref. [17], -1 MeV $\le \Delta m \le$ 4 MeV. In particular, for the value of Δm recommended in Ref. [2], $\Delta m \sim 3$ MeV, the final result would be $\Delta a_{CSB} = 1.67$ fm, compatible with the error bars of the experimental data.

In the case of the present chiral quark cluster model the proton–neutron mass difference is compatible with $\Delta m - 2.13$ MeV or -1.34 MeV, depending on the use of quadratic or linear confinement, respectively [2]. With these values for Δm, we obtain $\Delta a_{CSB} = 1.31$–1.37 fm, really close to the results obtained in Ref. [4]. As explained above, the ρ^0–ω mixing is discarded in chiral quark cluster

[1] As explained above, the Coulomb term does not generate any contribution in baryonic models. However, in the case of quark models it gives a contribution coming from the simultaneous exchange of photons and quarks between the baryons. Obviously this mechanism is not present if the quark substructure of baryons is not considered.

[2] Confinement, while not affecting the NN interaction, it has a great influence on the spectrum.

models as a possible source of CSB. Therefore, the proton–neutron mass difference in meson-exchange models provides similar results to those obtained in quark models when the QED–QCD interference terms are considered and the up–down constituent quark mass difference is taken to reproduce the neutron-proton mass difference. However, both mechanisms are completely different. While the quark-based terms providing the CSB splitting also give a significant contribution to CIB, in meson-exchange models none of the employed mechanisms to explain CSB contribute to CIB. As a consequence, a direct comparison is not reliable.

The success of the present approach suggests a further effort to explain charge-dependent effects as for example binding-energy differences of the $A=3$ sector or separation energies in the A = 4 one. However, these systems are enough complicated from the quark-model point of view as to make a straightforward generalization of the accurate calculations done in the present work for the two-body system. Therefore, although tempting, to make a thoughtful prediction for the three- or four-body systems based on the results presented here for the two-body system seems to be rather involved.

In summary, taking into account the pion-mass splitting, the quark-exchange Coulomb interaction and the QED–QCD interference terms it is possible to reproduce the charge independence breaking on the $^1S_0$ scattering length in a chiral quark cluster model without introducing any additional parameter to those necessary for describing the NN interaction. The contribution of the quark-exchange Coulomb interaction and the QED–QCD interference terms make also possible to explain the charge symmetry breaking on the scattering length. The influence of up–down constituent quark-mass difference, being small due to the cancellation among the different terms, is compatible with the values of Δm extracted from the hadron isomultiplet splittings.

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