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Nuclear forces and currents in large-N_C QCD

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Abstract. Expression of the nucleon-nucleon interaction to leading order in $1/N_C$ in terms of Fermi invariants allows a dynamical interpretation of the interaction and a consistent construction of the associated interaction currents. The numerically significant components of 4 different modern realistic phenomenological interaction models admit very similar meson exchange interpretations in the large-N_C limit. The ratio of the volume integrals of the leading, next-to-leading and next-to-next leading-order terms in these interaction models is roughly 300 : 5–10 : 0.1, which corresponds fairly well to the ratios of $1/N_C^2$ between the terms that would be suggested by the $1/N_C$ expansion if $N_C = 3$.

PACS. 13.75.Cs Nucleon-nucleon interactions (including antinucleons, deuterons, etc.) – 21.30.Cb Nuclear forces in vacuum

1 Introduction

The large color number limit of QCD allows a series expansion in $1/N_C$ for hadronic observables, where the first few terms capture the key phenomenological features of the structure of the baryons [1]. The leading terms in the $1/N_C$ series expansion of the components of the nucleon-nucleon interaction have been shown to correspond well with the strongly coupled exchange terms in a phenomenological meson exchange model for the interaction [2].

All the most commonly employed modern realistic phenomenological interaction models allow an interpretation in terms of phenomenological meson exchange and their numerically significant components correspond well to the leading terms in the $1/N_C$ expansion of the interaction components. The ratio of the volume integrals of the leading, next-to-leading and next-to-next leading-order terms in these interaction models is roughly $300 : 5-10 : 0.1$, which matches the ratios of $1/N_C^2$ between the terms that is suggested by the $1/N_C$ expansion for $N_C = 3$.

A dynamical interpretation of a phenomenological interaction model is possible if it is expressed in terms of the 5 Fermi invariants. That separates the interaction into linear combinations of scalar, vector, axial vector and pseudoscalar exchange mechanisms. These invariants define consistent interaction current operators [3,4], for which $1/N_C$ expansions follow from those of the corresponding potentials [5].

The nucleon-nucleon interaction models that are considered here are the V18 [6], the CD-Bonn [7], the Nijmegen(93) [8] and the Paris [9] potentials. All of these have long-range pion exchange tails, and phenomenological short-range terms. Their components in the Fermi invariant representation are remarkably similar in strength, and when parametrized in terms of single-meson exchange give rise to similar "effective" meson-nucleon couplings.

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2 The nucleon-nucleon interaction in the large-N_C limit

2.1 Phenomenological interactions

The nucleon-nucleon interaction is commonly expressed in terms of the following set of Galilean invariant spin and isospin operators:

$$V_{NN} = \sum_i^5 [\tilde{v}_j^+ + \tilde{v}_j^- \boldsymbol{\tau}^1 \cdot \boldsymbol{\tau}^2]\, \tilde{\Omega}_j, \tag{1}$$

where the coefficients $\tilde{v}_j^\pm$ are scalar functions and the spin operators $\tilde{\Omega}_j$ are defined as

$$\tilde{\Omega}_C = 1, \quad \tilde{\Omega}_{LS} = \boldsymbol{L}\cdot\boldsymbol{S}, \quad \tilde{\Omega}_T = S_{12},$$
$$\tilde{\Omega}_{SS} = \boldsymbol{\sigma}^1\cdot\boldsymbol{\sigma}^2, \quad \tilde{\Omega}_{LS2} = \frac{1}{2}\{\boldsymbol{\sigma}^1\cdot\boldsymbol{L}, \boldsymbol{\sigma}^2\cdot\boldsymbol{L}\}_+ \quad . \tag{2}$$

The powers of the leading terms in the $1/N_C$ expansion for these potential components are the following [2]:

$$\tilde{v}_C^+\tilde{\Omega}_C, \quad \tilde{v}_T^-\tilde{\Omega}_T, \quad \tilde{v}_{SS}^-\tilde{\Omega}_{SS} \quad \sim \quad \mathcal{O}(N_C),$$
$$\tilde{v}_C^-\tilde{\Omega}_C, \quad \tilde{v}_2^\pm\tilde{\Omega}_{LS}, \quad \tilde{v}_T^+\tilde{\Omega}_T, \quad \tilde{v}_{SS}^+\tilde{\Omega}_{SS}, \quad \tilde{v}_{LS2}^-\tilde{\Omega}_{LS2} \quad \sim \quad \mathcal{O}(1/N_C),$$
$$\tilde{v}_{LS2}^+\tilde{\Omega}_{LS2} \quad \sim \quad \mathcal{O}(1/N_C^3). \tag{3}$$

A simple derivation of these scaling relations is given below.

For a dynamical interpretation re-expression of the interaction in terms of the 5 Fermi invariants S, V, T, A, P is required. These are defined as [10]

$$S = 1, \quad V = \gamma_\mu^1 \gamma_\mu^2, \quad T = \frac{1}{2}\sigma_{\mu\nu}^1 \sigma_{\mu\nu}^2,$$
$$A = i\gamma_5^1\gamma_\mu^1 \, i\gamma_5^2\gamma_\mu^2, \quad P = \gamma_5^1\gamma_5^2. \tag{4}$$

In terms of the Fermi invariants the interaction takes the form

$$V_{NN} = \bar{u}(p_1')\bar{u}(p_2')[v_j^+ + v_j^- \, \boldsymbol{\tau}^1 \cdot \boldsymbol{\tau}^2] \, F_j \, u(p_1)u(p_2), \tag{5}$$

where the F_j, $j = 1...5$ represent the Fermi invariants in the order S, V, T, A, P.

The linear relation between the spin operators $\tilde{\Omega}_j$ and the Fermi invariants F_j is given (to order $1/m_N^2$) in ref. [4]. Since the nucleon mass $m_N \sim \mathcal{O}(N_C)$, only the leading terms in $1/m_N^2$ are needed for the present large-N_C limit considerations.

The N_C dependence of the components of the potential (1) may be inferred directly by quark model considerations. Consider the single quark operators $1, \sigma_j, \tau_k, \sigma_j\tau_k$. Matrix elements of the sum over N_C such quark operators in nucleon states then depend on N_C as follows [11]:

$$\langle N|\sum_{q=1}^{N_C} 1^q|N\rangle \sim N_C \,, \quad \langle N|\sum_{q=1}^{N_C} \sigma_j^q|N\rangle \sim N_C^0 \,,$$
$$\langle N|\sum_{q=1}^{N_C} \tau_k^q|N\rangle \sim N_C^0 \,, \quad \langle N|\sum_{q=1}^{N_C} \sigma_j^q\tau_k^q|N\rangle \sim N_C \,. \tag{6}$$

In the large-N_C limit the baryon-baryon interaction may be interpreted as meson exchange, since the gluon lines may be replaced by $q\bar{q}$ lines in all surviving (planar gluon) diagrams. The meson-baryon couplings are proportional to the quark operator matrix elements above and inversely proportional to the meson decay constants f_M, which scale like $\sqrt{N_C}$ [1]. Application of the scaling relations (6) and multiplication by $1/f_M^2$ to the two-nucleon system directly implies that

$$\tilde{v}_C^+\tilde{\Omega}_C, \quad \tilde{v}_T^-\tilde{\Omega}_T, \quad \tilde{v}_{SS}^-\tilde{\Omega}_{SS} \quad \sim \quad \mathcal{O}(N_C),$$
$$\tilde{v}_C^-\tilde{\Omega}_C, \quad \tilde{v}_T^+\Omega_T, \quad \tilde{v}_{SS}^+\tilde{\Omega}_{SS} \quad \sim \quad \mathcal{O}(1/N_C). \tag{7}$$

The order in N_C of the spin-orbit interaction may be found by noting that the momentum operator $\boldsymbol{P}$ in the spin-orbit interaction operator always appears in the combination $\boldsymbol{P}/m_N$, where $m_N \sim N_C$. The isospin-independent term $\tilde{v}_{LS}^+\tilde{\Omega}_{LS}$ contains the spin operator of one nucleon in combination with $\boldsymbol{P}/m_N$, and therefore the vertex scales as $1/N_C$. If the quark coupling at the other nucleon line is $\sim 1^q$, it follows that $\tilde{v}_{LS}^+\tilde{\Omega}_{LS} \sim \mathcal{O}(1/N_C)$ once the overall factor $1/f_M^2$ is taken into account. For the isospin-dependent spin-orbit interaction the scaling factor or the vertex with a spin operator multiplying $\boldsymbol{P}/m_N$ and an isospin operator is N_C^0. In this case the vertex at the other nucleon line also contains an isospin factor, so it also scales as N_C^0. Thus, it follows that $\tilde{v}_{LS}^-\tilde{\Omega}_{LS} \sim \mathcal{O}(1/N_C)$. The N_C scaling of the isospin independent quadratic spin-orbit interaction may be obtained by a direct extension of these arguments.

When the interaction is re-expressed in terms of Fermi invariant potential components $v_j^\pm$ as in ref. [4], with retention of only the leading terms in $1/m_N^2$ (*i.e.* in $1/N_C^2$) the order in $1/N_C$ of the terms is given in table 1 [5].

Table 1. Order of the leading term in the $1/N_C$ expansion of the Fermi invariant potential components.

Isospin	S	V	T	A	P
1	N_C	N_C	$1/N_C$	$1/N_C$	N_C
$\boldsymbol{\tau}^1 \cdot \boldsymbol{\tau}^2$	N_C	N_C	N_C	N_C	N_C^3

2.2 Dynamical interpretation of the potential components

The only isospin-independent potential components that are of order N_C are the scalar and vector components v_S^+ and v_V^+ as well as the pseudoscalar component v_P^+. The first one of these corresponds to the largest component in the two-pion exchange interaction between nucleons [12,13], which commonly is modeled in terms of a scalar ("σ") meson exchange mechanism [14,15]. The second corresponds to the short-range repulsion between nucleons, and is commonly modeled in terms of a ω meson exchange interaction, with an overstrength effective ω nucleon coupling constant [15]. The last (pseudoscalar) term, which may be interpreted as η meson exchange is large in the earlier potential models, but very small in the most recent models.

Among the isospin-dependent Fermi invariant potential components in table 1 the pseudoscalar component is of order N_C^3 and are thus the largest of all terms in the $1/N_C$ counting scheme. This strong pseudoscalar exchange component v_P^- is immediately interpretable in terms of the long-range pion exchange interaction between nucleons, which is expectedly "strong", because of its long range.

That the other isospin-dependent Fermi invariant potential components are of order N_C also corresponds to established nucleon-nucleon phenomenology. To see this, it is worth noting that an isospin 1 vector meson (ρ) exchange interaction may be expressed in terms of Fermi invariants as follows [16]:

$$\left(\gamma_\mu^1 - \frac{\kappa}{2m_N}\sigma_{\mu\nu}^1 \, k_\nu\right)\left(\gamma_\mu^2 + \frac{\kappa}{2m_N}\sigma_{\mu\alpha}^2 \, k_\alpha\right) = \frac{\kappa}{m_N^2}P_\mu^1 P_\mu^2 S$$
$$+(1+\kappa)V - \frac{\kappa(1+\kappa)k^2}{4m_N^2}T + \frac{\kappa(1+\kappa)}{m_N^2}P_\mu^1 P_\mu^2 P. \tag{8}$$

Phenomenological boson exchange interaction models typically contain a ρ-meson exchange interaction, where the "effective" tensor coupling of the ρ-meson to nuclei is large $\kappa \sim 7$ [15]. Because of the large tensor coupling, such an isospin-dependent vector meson exchange interaction contributes strongly to all the Fermi invariant potential components, except the axial vector invariant. The order N_C of the potential components v_S^-, v_V^-, v_T^- thus may be interpreted in terms of a strong ρ-meson exchange interaction.

While the isospin-dependent pseudoscalar potential $v_P^- P$ is of order N_C^3, the corresponding isospin-independent potential $v_P^+ P$ is only of order N_C. This corresponds to the phenomenological finding in boson exchange models for the nucleon-nucleon interaction that the η-meson exchange term is much weaker than the π-meson exchange interaction component.

3 Large-N_C components of phenomenological interaction models

The simplest numerical estimates of the potential components are their volume integrals. These are given in table 2 for the 4 considered interaction models. In the case of the V18 potential, the operator form of which contains a quadratic spin-orbit interaction of the form $(\boldsymbol{L}\cdot\boldsymbol{S})^2$, we employ the relation

$$(\boldsymbol{L}\cdot\boldsymbol{S})^2 = 2\boldsymbol{L}^2 + 2\tilde{\Omega}_{LS2} - 2\tilde{\Omega}_{LS} \qquad (9)$$

to reduce the interaction to the standard form (1) in combination with terms of the form $\boldsymbol{L}^2$.

In the case of the isospin-independent scalar interaction these volume integrals are all of the order 10 fm^2, ranging from $-6.3\,\mathrm{fm}^2$ for the Paris potential to -13.5 for the CD-Bonn potential.

If the isospin-independent scalar potential component is interpreted as due to a single scalar meson exchange interaction, the volume integral would equal $-g_S^2/m_S^2$, where g_S is the scalar meson-nucleon coupling constant, and m_S the scalar meson mass. If m_S is taken to be 600 MeV the value of the effective scalar meson coupling constant for these interactions range between 7.6 and 11.2 (table 3). It is striking how closely similar values obtain for the "effective" scalar meson coupling constants with the 4 different interaction models, two of which do not contain any scalar-meson–like term in their parametrized forms.

In a meson exchange interpretation the isospin-dependent scalar interaction arises from exchange of the $a_0(980)$ meson. The volume integrals of these interactions should equal $-g_{a_0}^2/m_{a_0}^2$, where g_{a_0} is the $a_0(980)$-nucleon coupling constant and m_{a_0} is the mass of the $a_0(980)$. If the value of the "effective" $a_0(980)$-nucleon coupling constant is extracted from these volume integrals, the values range from $g_{a_0} = 9.0$ to $g_{a_0} = 10.4$ (table 3).

The isospin-independent vector interaction admits an interpretation in terms of a repulsive ω-meson exchange interaction. The shape of this interaction component is very similar for all the interactions considered, and the volume integrals are also remarkably similar, ranging from 8.7 to 11.6 fm^2. If the "effective" ω-nucleon coupling constant is extracted from the volume integrals, by setting them equal to g_ω^2/m_ω^2 the values range between 11.7 and 13.5.

Table 2. Volume integrals (in fm^2) of the leading terms in the $1/N_C$ expansion of the Fermi invariant potential components phenomenological interaction models.

Component	V18	CD-Bonn	Nijmegen (93)	Paris
v_S^+	−8.7	−13.5	−10.3	−6.3
v_S^-	−3.2	−3.3	−3.3	−4.4
v_V^+	9.4	11.6	8.7	10.2
v_V^-	3.2	3.2	2.9	4.4
v_T^+	−0.1	0.0	0.0001	0.03
v_T^-	0.6	0.1	0.001	0.46
v_A^+	−0.1	0	0	0.03
v_A^-	0.6	0	0	0.46
v_P^+	9.8	0.0	0.35	18.0
v_P^-	360	338	323	352

Table 3. Effective meson-nucleon coupling values that correspond to phenomenological interaction models.

Component	V18	CD-Bonn	Nijmegen (93)	Paris
g_σ	9.0	11.2	9.8	7.6
g_{a_0}	9.0	9.0	9.0	10.4
g_ω	12.2	13.5	11.7	12.7
κ_ρ	7.0	7.0	6.3	10.1
g_η	8.7	0.0	1.8	11.7
g_π	13.4	13.0	12.7	13.2

The isospin-dependent vector interaction, by eq. (8), admits an interpretation in terms of ρ-meson exchange. This interaction component is roughly 3 times weaker than the corresponding isospin-independent interaction. The volume integrals of the isospin-dependent vector interaction range from 2.9 to 4.4 fm^2 for the 4 phenomenological interactions considered here. In a simple ρ-meson exchange model these volume integrals equal $(1+\kappa)g_\rho^2/m_\rho^2$, where g_ρ and κ are the vector and tensor ρ-nucleon coupling constants. The canonical value for the ρ-nucleon vector coupling constant is $g_\rho^2/4\pi \sim 0.5$. If this value for g_ρ is used in the expression for the volume integral, an "effective" value for κ_ρ can be determined. The volume integrals in table 2 for the 4 interaction models then give values for κ_ρ in the range 6.3–10.1, in agreement with the early finding that $\kappa_\rho \sim 6.6$ [17].

In a meson exchange model the tensor potential arises from vector meson exchange when the vector mesons couple to the nucleon with a Pauli (tensor) coupling. As in the CD-Bonn interaction model the isospin-independent ω-meson exchange interaction has no Pauli coupling term, v_T^+ vanishes in this interaction model.

By the N_C counting rules in table 1 the isospin-independent tensor interaction should be smaller by $1/N_C^2$ than the isospin-dependent tensor interaction.

Comparison of the corresponding set of volume integrals in table 2 shows that the phenomenological interaction models considered here satisfy this rule well.

The order N_C of the isospin-dependent tensor interaction alone does not explain why this interaction is one order of magnitude smaller than the corresponding vector interactions for all the phenomenological potential models. For boson exchange models the reason is readily seen in eq. (8), which shows that the tensor coupled vector meson exchange interaction is suppressed by an overall factor $1/m_N^2$, which is only partially counteracted by the large tensor coupling κ_ρ. For the phenomenological interaction models the reason for the weakness of the isospin-dependent tensor interaction is to be found in the fact that pion exchange gives rise to the bulk of the isospin-dependent spin-spin and vector interactions, and this pion (or pseudoscalar) exchange contribution is exactly cancelled in the combination of v_{SS}^- and v_T^-. This latter argument may also be extended to the isospin-independent tensor interaction, where the pseudoscalar —in this case the η-meson— exchange contribution cancels in the combination of v_{SS}^+ and v_T^+.

In single-meson exchange models only axial vector meson exchange gives rise to an axial vector interaction. Since the CD-Bonn and the Nijmegen (93) boson exchange interaction models do not contain any a_1-meson exchange terms, these interaction models have no axial vector exchange components. The phenomenological V18 and Paris potential models give rise to small A interaction components. These satisfy the N_C counting rules in table 1, by which the isospin-dependent axial vector interaction should be larger by N_C^2 than the isospin-independent one as seen in table 2.

In a single-meson exchange interpretation the longest-range mechanism that contributes to the isospin-independent pseudoscalar interaction, is η-meson exchange. This interaction component is not well constrained by nucleon-nucleon scattering data. As a consequence the phenomenological interaction models considered here give widely different results for this interaction component.

The η-nucleon coupling constant is not well known. An estimate for this coupling constant may be obtained from the volume integrals of the phenomenological interaction models if these are set to equal g_η^2/m_η^2. From the volume integral values listed in table 2 one then obtains values for g_η, which range from 1.8 (Nijmegen (93)) to 11.7 (Paris) (table 3). Analyses of observables, other than nucleon-nucleon scattering as, *e.g.*, η-meson photoproduction suggest that the coupling constant value should not exceed 2.2 [18].

The isospin-dependent pseudoscalar exchange interaction is strong and has long range. Its main component is the long-range pion exchange interaction, which is built into all the phenomenological interaction models considered here. Because of this all the interaction models converge for nucleon separations larger than 1 fm. This interaction component is also the strongest component by N_C counting, as it scales as N_C^3 (table 1). The volume integrals of this interaction component are listed in table 2 for the 4 interaction models considered, and range from 323 fm^2 to 360 fm^2. The corresponding values for the pseudoscalar pion-nucleon coupling constant g_π range from 12.7 to 13.4, when extracted by equating the numerically determined volume integrals with g_π^2/m_π^2 (table 3).

4 Exchange currents in the large-N_C limit

The scaling rules (6) may be applied to give the large-N_C scaling behavior of both the single-nucleon current operators as well as of the exchange currents that are associated with the interaction (1) [5]. As an example the axial current and charge operators of a single nucleon,

$$\boldsymbol{A}_\pm = -g_A \boldsymbol{\sigma} \tau_\pm, \quad A_\pm^0 = -g_A \frac{\boldsymbol{\sigma}\cdot\boldsymbol{p}}{m_N}\tau_\pm, \tag{10}$$

are of order N_C^1 and N_C^0, respectively.

There is no axial exchange charge operator that would be directly proportional to the pseudoscalar invariant potential component. There is, however, an axial exchange charge operator, which is of order N_C^0, and which arises from the long-range pion exchange interaction, which gives rise to the bulk of the pseudoscalar interaction component. This axial charge operator was derived in ref. [19], and has the form

$$A_\pm^0(\pi) = \frac{g_A}{4\pi}\left(\frac{m_\pi}{2f_\pi}\right)^2 \boldsymbol{\Sigma}_{12}\cdot\boldsymbol{r}_{12}(\boldsymbol{\tau}^1\times\boldsymbol{\tau}^2)_\pm \times\left(1+\frac{1}{m_\pi r_{12}}\right)\frac{e^{-m_\pi r_{12}}}{m_\pi r_{12}}, \tag{11}$$

where $\boldsymbol{\Sigma}_{12} = \boldsymbol{\sigma}^1 + \boldsymbol{\sigma}^2$. Because the pion decay constant $f_\pi \sim \sqrt{N_C}$ in the large-N_C limit, it is readily seen by the relations (6) that this operator is of order N_C^0.

The contributions of the two-nucleon exchange current terms to the axial charge operator are conventionally expressed in the form of an effective single-nucleon axial charge operator. The exchange current contributions then represent nuclear enhancement factors of the single-nucleon axial charge operator (10). Experimental studies of first-forbidden nuclear β-transitions reveal that this enhancement factor runs from about 1.7 in light nuclei [20] to about a factor 2 in heavy nuclei [21]. About one half of this enhancement may be attributed to the pion exchange operator (11), which is natural as its order in the $1/N_C$ expansion is the same as that of the single-nucleon operator (10). The bulk of the remainder arises from the exchange current, which is associated with the isospin-independent scalar interaction [3]. While the order of this term is $1/N_C$, it gives rise to a direct term matrix element, which enhances its value relative to that of the matrix element of the pion exchange term (11), which is an "exchange term".

A complete list of the N_C dependence of the axial and electromagnetic exchange current operators that are associated with the interaction components in the Fermi representation is given in [5], along with explicit expressions for the corresponding potential components.

5 Discussion

This analysis of 4 commonly employed phenomenological nucleon-nucleon interaction models reveals that the structure of their components is completely consistent with their corresponding dependence on N_C (or $1/N_C$). For all the interaction models the isospin-dependent pseudoscalar components, which contain the long-range pion exchange interaction, have volume integrals that are larger than those of any other interaction component by more than an order of magnitude. This interaction component also scales with the largest power of N_C (N_C^3) (table 2).

The interaction components that follow the isospin-dependent pseudoscalar interaction in strength are the isospin-independent scalar and vector interactions, which scale as N_C. These interaction components are those responsible for nuclear binding (v_S^+) and short-range repulsion between nucleons (v_V^-). For distances shorter than 0.4 fm the variation in form of these interaction components between the 4 considered phenomenological interaction models is substantial [5].

Next in strength are the isospin-dependent scalar and vector interactions, which also scale as N_C. The volume integrals of these interaction components are about half as large as those of the corresponding isospin-independent interactions.

The tensor and axial vector interaction components are very weak for all the considered phenomenological interaction models. For the isospin-independent tensor and axial vector components this is completely consistent with their N_C dependence, which is $1/N_C$. The smallness of the isospin-dependent tensor and axial vector exchange interaction components cannot be explained by their N_C dependence alone, as they scale as N_C. In meson exchange models the smallness of v_T^- is however natural, as it arises from tensor coupled vector mesons, and contains an overall factor $1/m_N^2$ (8).

The least well-understood interaction component is the isospin-independent pseudoscalar interaction. This component, which scales as N_C^1, is vanishingly small in two of the considered phenomenological interactions and even stronger than v_V^+ in the other two. The longest-range part of this interaction component arises from η-meson exchange. The large variation between the phenomenological interaction models for this interaction component reflects the continuing uncertainty concerning the strength of the η-nucleon coupling.

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