CHIRAL SYMMETRY AND THE NUCLEON-NUCLEON INTERACTION[1]

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Abstract

The main progress in the field of nucleon-nucleon (NN) potentials, which we have seen in recent years, is the construction of some very quantitative (high-quality/high-precision) NN potentials. These potentials will serve as excellent input for microscopic nuclear structure calculations and will allow for a systematic investigation of off-shell effects. After this enormous quantitative work, it is now time to re-think the NN problem in fundamental terms. We need a derivation of the nuclear force which observes Lorentz invariance and the symmetries of QCD.

Current Status of NN Potentials

The New High-Precision NN Potentials. In 1993, the Nijmegen group published a phase-shift analysis of all proton-proton and neutron-proton data below 350 MeV lab. energy with a χ^2 per datum of 0.99 for 4301 data [1]. Based upon this analysis, charge-dependent NN potentials have been constructed by the Nijmegen [2], the Argonne [3], and the Bonn (CD-Bonn [4]) groups which reproduce the NN data with a χ^2/datum ≈ 1 (see Table 1). The main difference between these new potentials is that some are local and some non-local.

Ever since NN potentials have been developed, local potentials have enjoyed great popularity because they are easy to apply in configuration-space calculations. Note, however, that numerical ease is not a proof for the local

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Table 1: Recent high-precision NN potentials and predictions for the two- and three-nucleon system.

	CD-Bonn[4]	Nijm-II[2]	Reid'93[2]	V_{18}[3]	Nature
Character	non-local	local	local	local	non-local
χ^2/datum	1.03	1.03	1.03	1.09	–
$g_\pi^2/4\pi$	13.6	13.6	13.6	13.6	13.75(25)
Deuteron properties:					
Quadr. moment (fm^2)	0.270	0.271	0.270	0.270	0.276(3)^a
Asymptotic D/S state	0.0255	0.0252	0.0251	0.0250	0.0256(4)
D-state probab. (%)	4.83	5.64	5.70	5.76	–
Triton binding (MeV):					
non-rel. calculation	8.00	7.62	7.63	7.62	–
relativ. calculation	8.19	–	–	–	8.48

^{a} Corrected for meson-exchange currents and relativity.

nature of the nuclear force. In fact, any deeper insight into the reaction mechanisms underlying the nuclear force suggests a non-local character. In particular, the composite structure of hadrons should lead to large non-localities at short range. But, even the conventional and well-established meson theory of nuclear forces—when derived properly relativistically and without crude approximations—creates a non-local interaction.

In Fig. 1, we show the half off-shell $^3S_1$–$^3D_1$ potential that can be produced only by tensor forces. The on-shell momentum q' is held fixed at 153 MeV (equivalent to 50 MeV lab. energy), while the off-shell momentum q runs from zero to 1400 MeV. The on-shell point ($q = 153$ MeV) is marked by a solid dot. The solid curve is the new relativistic one-boson-exchange (OBE) potential, CD-Bonn [4]. When the relativistic one-pion-exchange (OPE) amplitude is replaced by the static/local approximation the dashed curve is obtained. When this approximation is also used for the one-ρ exchange, the dotted curve results. It is clearly seen that the static/local approximation substantially increases the tensor force off-shell. Obviously, relativity and non-locality are intimately interwoven.

In Table I (upper part), we summarize some important two-nucleon properties as predicted by the new high-quality potentials. Using the same πNN coupling constant, all potentials predict almost identical deuteron observables (quadrupole moment and asymptotic D/S state normalization). Note,

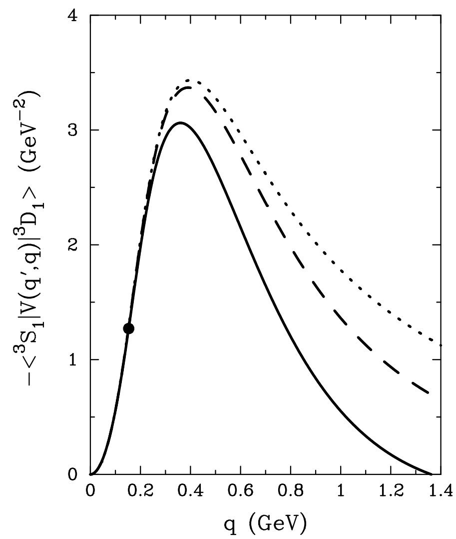

Figure 1: Half off-shell $^3S_1$–$^3D_1$ amplitude for the relativistic CD-Bonn potential (solid line). The dashed curve is obtained when the local approximation is used for the one-pion-exchange (OPE) and the dotted curve when OPE and one-ρ exchange are both local. $q' = 153$ MeV.

however, that the (un-observable) deuteron D-state probability comes out significantly larger for the local potentials ($\approx 5.7\%$) as compared to the non-local CD-Bonn potential (4.8%). Obviously, the deuteron D-state probability is kind of a numerical measure for the off-shell strength of the tensor force, shown graphically in Fig. 1.

Off-Shell NN Potential and Nuclear Structure. By construction, NN interactions reproduce the two-nucleon scattering data and the properties of the deuteron. Assuming the existence of NN scattering data of increasing quantity and quality, the NN interaction can be fixed with arbitrary accuracy—"on the energy shell" (on-shell). However, in nuclear structure the NN potential contributes also off-shell. For several decades, the qustion has been around, how large the effects can be that come from differences in the off-shell behavior of different NN potentials when applied in microscopic nuclear structure calculations. The recent construction of high-precision NN potentials has finally set the stage for a reliable investigation of the issue.

Friar *et al.* [5] have calculated the binding energy of the triton (in charge-dependent 34-channel Faddeev calculations) applying the new, high-quality

Nijmegen and Argonne potentials and obtained almost identical results for the various local models, namely, 7.62 ± 0.01 MeV (experimental value: 8.48 MeV), where the uncertainty of ± 0.01 MeV is the variation of the predictions which occurs when different local potentials are used. The smallness of the variation is due to the fact that all the local potentials have essentially the same off-shell behavior.

Using the new, non-local CD-Bonn potential, we have performed a (34-channel, charge-dependent) Faddeev calculation for the triton and obtain 8.00 MeV binding energy (cf. Table I). This is 0.38 MeV more than local potentials predict. The unaquainted observer may be tempted to believe that this difference of 0.38 MeV is quite small, almost negligible. However, this is not true. The difference between the predictions by local potentials (7.62 MeV) and experiment (8.48 MeV) is 0.86 MeV. Thus, the problem with the triton binding is that 0.86 MeV cannot be explained in the simplest way, that is all. Therefore, any non-trivial contribution must be measured against the 0.86 MeV gap between experiment and simplest theory. On this scale, the non-locality considered in this investigation explains 44% of the gap; i. e., it is substantial with respect to the discrepancy.

The above three-body results were obtained by using the conventional non-relativistic Faddeev equations. However, since CD-Bonn is a relativistic potential, one can also perform a relativistic Faddeev calculation by extending the relativistic three-dimensional Blanckenbecler-Sugar formalism to the three-body system [6]. The binding energy prediction by CD-Bonn then goes up to 8.19 MeV. This further increase can be understood as an additional off-shell effect from the relativistic two-nucleon t-matrix applied in the three-nucleon system.

The trend of the non-local Bonn potential to increase binding energies has also a favorable impact on predictions for nuclear matter [7] and ground/excited states of nuclei [8].

Chiral Symmetry and the Nuclear Force

Introduction. The nuclear force is a sample of strong interactions. The fundamental theory of strong interactions is QCD. Thus, ideally, the NN interaction should be derived directly from QCD.

The last decade has seen numerous attempts to derive the nuclear force from QCD or "QCD-inspired" models—with mixed success. The suggestion has then been made, to take an alternative attitude, namely: If we can't solve QCD, then let's at least observe its symmetries, particularly, chiral symmetry. The most outstanding advocate of this view is S. Weinberg [9].

Past models for the NN interaction do not have any clear relationship with chiral symmetry. Since all NN models fit the data, they are also not in gross violation of chiral symmetry. The best example for this 'accidental' compliance with chiral symmetry is the fact that essentially all field-theoretic models for the NN interaction leave out pair terms—because they don't fit.

A recent fundamental progress in nuclear physics is that chiral symmetry is now taken seriously. Therefore, it is about time to relate the NN interaction to chiral symmetry in a way which is better than just accidental.

Even though a review article entitled "Chiral Symmetry and the Nucleon-Nucleon Interaction" was published already some 17 years ago [10], there have been few serious attempts to pursue this line of research [11].

Very recently, by initiative of Steven Weinberg [12], a group at the University of Texas [13] has derived a NN potential using chiral perturbation theory. In this work, the properties of the deuteron and the NN phase shifts below 300 MeV lab. energy are reproduced qualitatively using 26 parameters. The significance of this work is that it represents the first comprehensive attempt to strictly base the NN interaction on chiral symmetry. Even though this attempt can been deemed as basically successful, there are reasons for concern.

Conventional field-theoretic models for the NN interaction have typically 12 parameters and yield an accurate fit of the deuteron and NN scattering up to about 300 MeV. The Texas potential [13] has twice as many parameters and, nevertheless, provides only a qualitative fit. The qualitative nature of the fit makes this potential unsuitable for nuclear structure applications.

Of even more concern is another point: the Texas model [13] is nonrelativistic. We have seen in our above discussion on off-shell effects in nuclear structure that off-shell momenta up to about 2 GeV are important, making a relativistic approach mandatory. Moreover, the proper explanation of nuclear saturation requires a relativistic approach [7].

What is an Appropriate Lagrangian? Thus, we need a Lagrangian which fulfils the following minimal requirements (besides the usual ones, like, parity conservation and inclusion of nucleons):

- Lorentz invariance,
- (approximate) chiral symmetry,
- inclusion of (heavy) vector bosons.

Note that this 'minimal' program in regard to what is needed for a realistic nuclear interaction is, in fact, a maximal program in terms of chiral symmetry. First work on chiral symmetry in nuclear physics typically considered only pions and interactions between them. In the next step, also baryons were included, which was already a big and difficult step. Now, we even want to include (heavy) vector bosons. So far there is little work in this direction; which makes it a real challenge. Note that the inclusion of heavy bosons is crucial for a realistic description of the nculear force. One reason why the Texas potential is not doing too well in quantitative terms inspite of its large number of parameters may be the omission of vector bosons.

Recently, Furnstahl, Serot, and Tang [14] have proposed the following Langrangian which fulfils all of the above requirements:

$$\begin{aligned}
\mathcal{L} \;=\; & \bar{N}(i\gamma^\mu \mathcal{D}_\mu + g_A \gamma^\mu \gamma_5 a_\mu - g_\omega \gamma^\mu \omega_\mu - M)N \\
& -\frac{f_\rho}{4M}\bar{N}\rho_{\mu\nu}\sigma^{\mu\nu}N - \frac{f_\omega}{4M}\bar{N}\omega_{\mu\nu}\sigma^{\mu\nu}N \\
& +\frac{F_\pi^2}{4}tr(\partial_\mu U \partial^\mu U^\dagger) - \frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} + \frac{1}{2}m_\omega^2 \omega_\mu \omega^\mu \\
& -\frac{1}{2}tr(\rho_{\mu\nu}\rho^{\mu\nu}) + m_\rho^2 tr(\rho_\mu \rho^\mu) - g_{\rho\pi\pi}\frac{2F_\pi^2}{m_\rho^2}tr(\rho_{\mu\nu}v^{\mu\nu}) + \cdots
\end{aligned} \tag{1}$$

with

$$\begin{array}{lcllcl}
\pi & \equiv & \boldsymbol{\tau}\cdot\boldsymbol{\pi}/2 & \mathcal{D}_\mu & = & \partial_\mu + iv_\mu + ig_\rho \rho_\mu \\
\xi & = & e^{i\pi/F_\pi} & v_\mu & = & -\frac{i}{2}(\xi^\dagger \partial_\mu \xi + \xi \partial_\mu \xi^\dagger) \\
U & = & \xi\xi & a_\mu & = & -\frac{i}{2}(\xi^\dagger \partial_\mu \xi - \xi \partial_\mu \xi^\dagger) \\
\rho_\mu & \equiv & \boldsymbol{\tau}\cdot\boldsymbol{\rho}_\mu/2 & v_{\mu\nu} & = & \partial_\mu v_\nu - \partial_\nu v_\mu + i[v_\mu, v_\nu] \\
\sigma_{\mu\nu} & \equiv & \frac{i}{2}[\gamma_\mu, \gamma_\nu] & \tilde{D}_\mu \rho_\nu & \equiv & \partial_\mu \rho_\nu + i[v_\mu, \rho_\nu] \\
\omega_{\mu\nu} & = & \partial_\mu \omega_\nu - \partial_\nu \omega_\mu & \rho_{\mu\nu} & = & \tilde{D}_\mu \rho_\nu - \tilde{D}_\nu \rho_\mu + ig[\rho_\mu, \rho_\nu]
\end{array} \tag{2}$$

where $N = \begin{pmatrix} p \\ n \end{pmatrix}$ is the nucleon field with p and n the proton and neutron fields, respectively; $\boldsymbol{\pi}$ are the Goldstone pion fields which form an isovector, and $\boldsymbol{\rho}$ are the rho-meson fields. ω_μ is the field of the omega meson which can be considered as a chiral singlet in chiral SU(2) symmetry. $F_\pi \approx 93$ MeV is the pion decay constant, $g_A \approx 1.26$ is the axial coupling constant, and M denotes the nucleon mass. g_ρ is the vector-coupling constant of the ρ meson to the nucleon and f_ρ is the tensor-coupling constant; similarly for the ω. m_ρ and m_ω are the masses of the ρ and ω mesons, respectively. $g_{\rho\pi\pi}$ is the $\rho\pi\pi$ coupling constant.

The Lagrangian Eq. (1) is essentially based upon the classic papers by Weinberg [15] as well as Callan, Coleman, Wess, and Zumino [16].

The ellipsis in Eq. (1) stands for higher-order terms involving additional powers of the vector fields and their derivatives, and other terms consistent with chiral symmetry. For example, so-called 'contact' terms of the kind $\bar{N}N\bar{N}N$ and $\bar{N}\gamma_\mu N\bar{N}\gamma^\mu N$ are permitted by chiral symmetry. However, these terms could be absorbed by the exchange of a scalar-isoscalar boson and the omega meson, respectively, which may be justified by the success of the one-boson-exchange model for the NN interaction.

For the intermediate range attraction of the nuclear force, there are two suitable scenarios: it can be constructed from correlated two-pion exchange (as implied by the pion terms in the above Langrangian) [17]; or a scalar-isoscalar field (to approximate the correlated two-pion exchange) can be introduced in such a way as to maintain chiral symmetry; note that this scalar field is not the chiral partner of the pion.

When applying the Langrangian Eq. (1) to the NN problem, suitable expansion parameters have to be identified. This could be patterned after chiral perturbation theory. Naive dimensional analysis and the assumption of "naturalness" for the coupling constants could serve as guidelines. However, since this is a relativistic approach, there are characteristic differences to chiral perturbation theory and, therefore, the details still have to be worked out. It is suggestive to consider an expasion in powers of the fields and their derivatives.

In lowest order, the Lagrangian Eq. (1) will recover the terms familiar from the traditional one-boson-exchange model (however, with the pion coupled to the nucleon via gradient coupling). Higher orders will generate new terms characteristic for the chiral approach. These terms have to be

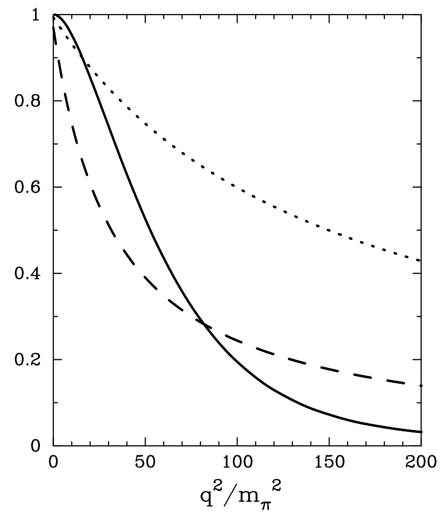

Figure 2: Comparison of different πNN form factors. The solid line represents the form factor extracted from the Skyrme model. The dashed and dotted lines are conventional monopole form factors with cutoff masses $\Lambda = 0.8$ and 1.7 GeV, respectively.

identified systematically and, then, added to the two-nucleon scattering and bound state problem. In this way, a relativistic NN model consistent with chiral symmetry will be developed step by step, and checked against the experimental NN data.

The πNN Form Factor. Analyzing the meson-baryon scattering S-matrix in the soliton sectors of effective, chiral Lagrangians does not require to consider separately meson-baryon form factors (FFs) because the soliton solution takes care of the spatial structure of the interaction in a consistent way [18]. This holds, of course, also for the analysis of the baryon-baryon interaction. Thus, one can extract meson-baryon FFs from soliton solutions of mesonic actions, which would allow for a comparison with FFs typically used in conventional meson-exchange models of the baryon-baryon interaction. Early work on this topic yielded rather disappointing results: The values for the cutoff mass Λ of an equivalent monopole cutoff came out to be around 0.6–0.8 GeV which is less than half of the 1.3–1.7 GeV typically required in OBE models for the NN interaction [7].

However, inspection of πN P-wave scattering [18] shows that the FF which actually determines the dominant part of the scattering amplitude contains an additional *metric factor* which has a profound influence on its shape, such that it is no longer compatible with the monopole form. As demonstrated in Fig. 2, the FF extracted from the Skyrme model (solid line) has a very small slope near $q^2 = 0$ and the curvature is negative. This means that for small q^2 the effective πNN coupling strength stays much closer to its value at $q^2 = -m_\pi^2$ than for comparable monopole FFs.

We have investigated to which extent such FF could be helpful in conventional meson-exchange potentials for nucleon-nucleon scattering and the structure of nuclei. It is well known that soft ($\Lambda \approx 0.8$ GeV) monopole FFs fail in the NN system, since they cut out too much of the tensor force provided by the pion: the deuteron quadrupole moment and asymptotic D/S state ratio and the ϵ_1 mixing parameter of NN scattering (which all depend crucially on the nuclear tensor force) come out too small [7]. First results indicate that the very hard behaviour of the Skyrme model FF for small q^2 is extremely useful in the OBE model for the NN interaction. On the other hand the very soft behaviour for $q^2 > 50\ m_\pi^2$ cuts off higher momenta much more efficiently than typical hard monopole FFs (cf. Fig. 2).

A consequence of this is that the Skyrme FF allows to describe the πN and NN system quantitatively with the *same* FF. Note that this is not possible with soft monopole FF unless a heavy pion, $\pi'(1200)$ (representing $\pi - \rho$ correlations), is introduced.

Summary

Several high-quality/high-precision NN potentials are now available which fit the low-energy NN data with idential perfection. These potentials differ, however, in their off-shell behavior. Thus, the stage is set for a systematic investigation of off-shell effects in microscopic nuclear structure.

After the excessive quantitative work on 'perfect' NN potentials which we have seen during the past five years, it is now time to sit back and *think* again—about the more fundamental aspects concerning the nuclear force. We need a derivation of the nuclear force which is Lorentz invariant and consistent with the symmetries of QCD.

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