THE SHORT-RANGE PART OF THE NN-INTERACTION QUARK-GLUON VERSUS MESON EXCHANGE+)

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It is shown that the concept of large nucleon bags ($R \geq 0.8$ fm) suppresses essential features of the meson exchange picture, which are needed in order to describe empirical NN data. It is investigated whether genuine quark-gluon-exchange processes can provide the characteristic features conventionally obtained from vector-meson exchange.

1. Introduction

Many examples in the literature now clearly reveal the fact that the picture of meson exchange is able to provide a convenient parametrization of the empirical low-energy ($E_{lab} \leq 300$ MeV) data. In fact, as Dr. R. Machleidt demonstrated in the foregoing talk, the latest version of the Bonn potential, which contains an explicit model for the 2π-exchange contribution consistent with what is known from dispersion theory and, in addition, corresponding $\pi\rho$-exchange diagrams, describes the NN scattering phase shifts very well, solely in terms of meson-nucleon coupling constants and cutoff-masses, i.e. physical parameters, which can (and should) be determined from the underlying quark-gluon structure of hadrons.

The advantage of keeping the meson-exchange expressions throughout the whole region, only supplementing them by form factors which are anyhow dictated by the quark structure, should be obvious: In this way, one can really demonstrate how far meson exchange works and where it breaks down. Surprisingly enough, our model works down to rather small distances.

+) Supported in part by Deutsche Forschungsgemeinschaft (Az.:Ho 730/5-1)

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Furthermore, our calculations have clearly shown that some structure of the nucleon (characterized by a cutoff-mass $\Lambda \simeq 1.5$ GeV corresponding to a radius of about 0.4 fm) has to be implemented in order to account for the empirical data.

These results suggest that the meson exchange picture be essentially valid; the remaining task would be to justify the meson-nucleon vertices quark-theoretically. (We will demonstrate later that possible discrepancies inside 0.5 fm do not influence the empirical data). Also, since a rather small radius of the nucleon is implied, a meson--theoretic treatment of nuclear structure problems should then be reliable.

On the other hand, some current bag models (e.g. the Cloudy Bag Model[1]) predict a nucleon radius of about 0.8 fm. Such a large value wipes out essential, characteristic features of the meson-exchange picture, and a reasonable description of the empirical data is not possible anymore in the conventional framework. Instead, genuine quark-gluon-exchange processes, which occur in the overlapping region of the nucleon bags, should be considered, and it is an interesting question whether such processes can provide the necessary features conventionally obtained from meson exchange. This will be the main topic of this talk.

If such rather large extensions of hadrons will be confirmed (e.g. by lattice gauge calculations), then meson-exchange provides only a phenomenological description and the physical picture is completely different. In this case, of course, an extension of meson exchange to other physical systems is at least questionable.

2. πNN vertex and NN data

In this chapter, we will shortly discuss predictions for the πNN vertex given by current bag-type models. Its general structure is

$$v_{k,i} \simeq F_R(k)\,\underset{\sim}{\sigma}\cdot\underset{\sim}{k}\,\tau_i \qquad (2.1)$$

where $\underset{\sim}{k}$ is the momentum of the pion and $\underset{\sim}{\sigma}$, τ_i denote the usual (nucleon) spin and isospin operators. The form factor $F_R(k)$ is given explicitly by

$$F_R(k) = 3\,\frac{j_1(kR)}{kR} \tag{2.2}$$

R being the bag radius. To a good approximation (as we will see below), $F_R(k)$ can be written in the usual monopole-type form

$$F_R(k) \simeq \frac{\Lambda_R^2}{\Lambda_R^2+k^2} \tag{2.3}$$

where the cutoff-parameter Λ_R is related to the bag radius by $\Lambda_R = \sqrt{10}\cdot R^{-1}$.

In the Cloudy Bag Model, R has been fixed from pion-nucleon scattering to be $R \simeq 0.8$ fm, which implies $\Lambda_R \simeq 800$ MeV. In a different type of approach, Weise et al.[2] found for the form factor

$$F_\Lambda(k) = e^{-\,k^2/\Lambda^2} \tag{2.4}$$

with values of Λ being in the same range as for the Cloudy Bag Model. Again, eq. (2.4) can be well approximated by eq. (2.3).

Fig. 1 shows the strong influence of the form factor with such a small cutoff mass, i.e. $\Lambda = 800$ MeV. In the important region around 1 fm, it suppresses the pion tensor interaction by almost a factor of 2. Values of $\Lambda \simeq 1.5$ GeV, which are needed in order to fit the empirical data, start to give an appreciable modification at much smaller distances.

Fig. 2 shows the influence of a strong pion cutoff on two selected partial wave phase shifts. Starting from an OBE-model which fits the scattering data and uses a cutoff-mass of $\Lambda = 1530$ MeV[3] at all vertices, it is seen that a value of $\Lambda = 800$ MeV for the πNN-vertex destroys the fit in a characteristic way: One phase shift moves up, the other one goes down. It is important to note that such a defect cannot be cured by a change of other parameters in the model.

Two additional conclusions can be drawn from this figure: First, the forms eq. (2.2, 2.4) have essentially the same effect on the phase shifts considered; second, the monopole form, eq. (2.3), is a sufficiently good approximation.

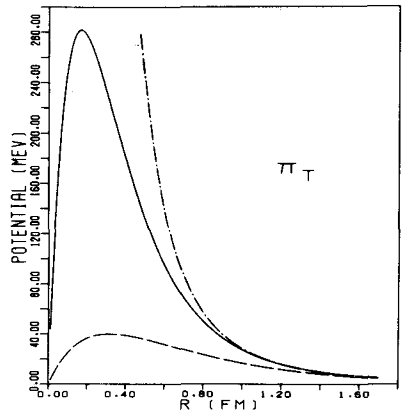

Fig. 1

One-pion-exchange tensor force (in MeV) as function of the distance R (in fm) between two nucleons. For the dash-dot curve, no form factor is used, whereas for the solid (dashed) curve, a monopole form factor, eq. (2.3), with Λ = 1530 (800) MeV is added.

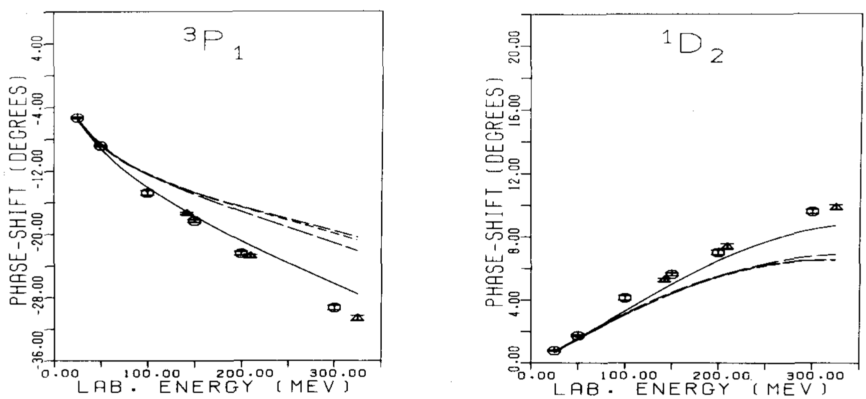

Fig. 2

NN scattering phase shifts (in degrees), in the $^3P_1$ and $^1D_2$ channel, as function of the nucleon lab energy (in MeV). The solid lines are obtained from an OBEP[3)], based on a form factor, eq. (2.3), with Λ_α = 1530 MeV for all mesons exchanged. The long-dashed lines are obtained if Λ_π = 800 MeV is used in eq. (2.3). The medium-dashed curves result from the use of the form factor in eq. (2.2), with R = 0.8 fm. The short-dashed lines originate from the form factor, eq. (2.4), with Λ = 800 MeV.

Thus, in the conventional boson-exchange framework, there is a lower limit for the cutoff mass Λ still allowing a good fit to the data. It was observed already in ref.[3] that this limit is around 1200 MeV. Similar conclusions were reached by Ericson and Rosa-Clot[4] in the context of the asymptotic D/S ratio of the deuteron.

In summary, nucleon radii R > 0.8 fm, suggested e.g. by the Cloudy Bag Model[1], lead to a strong suppression of boson-exchange contributions, destroying the beautiful description provided by such models. This fact as such, however, does not rule out large bag radii. Instead, it leads to the fascinating question whether genuine quark-gluon-exchange processes, which should occur in the overlapping region of the nucleon bags and must be taken into account, might be able to provide the necessary features conventionally obtained from the meson-exchange picture.

3. Quark-gluon versus meson exchange

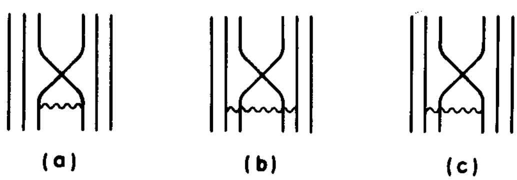

Fig. 3

Various one-gluon-exchange processes in the NN problem.

The one-gluon-exchange processes between two nucleon clusters, shown in fig. 3, represent a convenient starting point. Due to asymptotic freedom, they might be able to describe the short-range part of the NN interaction, i.e. to replace conventional vector-meson exchange, which is almost completely suppressed in case of large bag radii.

In fact, the isospin structure of the simplest one-gluon-exchange process, fig. 3 (a), is in remarkable agreement with the isospin dependence of the short-range part of the NN interaction provided by $(\omega+\rho)$-meson exchange[5]. (Note that ω provides the isoscalar, ρ the isovector part). We stress that this result is very basic, i.e. it depends only on the structure of diagram 3 (a). It is essential that the elementary (direct) quark-quark amplitude is flavour-independent and that there is no direct first-order process, i.e. quarks have to be interchanged. The result does not depend on specific model assumptions about the underlying quark-quark interaction and radial cluster wave functions. These features enter if the study is extended to the spin-dependence and to the other relevant processes (fig. 3 (b,c)). The spin-isospin structure and radial behaviour of the effective NN interaction resulting from processes in fig. 3 is suitably investigated in the Born-Oppenheimer approximation. In this treatment, the NN interaction V_{NN} is defined as the expectation value of the energy of the six-quark system minus the energy at infinite separation of the two clusters

$$V_{NN} \equiv \frac{\langle\psi| H_A+H_B+\sum_{i=1}\sum_{j=4}^{6} V(ij)|\psi\rangle}{\langle\psi|\psi\rangle} - 2\langle\phi_A|H_A|\phi_A\rangle \ . \qquad (3.1)$$

Here $|\psi\rangle$ is a totally antisymmetric six-quark state, $|\psi\rangle \equiv A|\phi_A\phi_B\rangle$ where ϕ_N is the antisymmetric and normalized nucleon cluster wave function consisting of a space, spin-isospin and colour part. $H_{A,B}$ is the internal Hamiltonian of cluster A,B, i.e.

$$H_A = \sum_{i=1}^{3} t_i + \sum_{\substack{i,j=1 \\ j>i}}^{3} V(ij) - T_A^{CM}$$

with t_i being the kinetic energy operator of quark i and T_A^{CM} the corresponding c.m. energy of cluster A. V_{NN} can be split up into $V_{NN} = V_{NN}^{(1)}+V_{NN}^{(T)}+V_{NN}^{(P)}$. The first term, $V_{NN}^{(1)}$, arises from the interactions between the two clusters characterized by the processes of fig. 3. $V_{NN}^{(T,P)}$ are (non-negligible) correction terms which take the difference of the kinetic (T) and potential (P) cluster energy inside the six-quark system compared to the three-quark cluster into account.

An evaluation of eq. (3.1) has been performed[6] using an underlying quark-quark interaction

$$V(ij) = V_{OGE}(ij) + V_{conf}(ij)$$

$$V_{OGE}(ij) = \underset{\sim}{\lambda}_i \cdot \underset{\sim}{\lambda}_j \frac{\alpha_s}{4} \left[\frac{1}{r_{ij}} - \frac{2}{3}\frac{\pi}{m^2}\,\delta(\underset{\sim}{r}_{ij})\underset{\sim}{\sigma}_i \cdot \underset{\sim}{\sigma}_j\right]$$

$$V_{conf}(ij) = -\underset{\sim}{\lambda}_i \cdot \underset{\sim}{\lambda}_j a r_{ij}^2$$

and

$$\varphi_A = \left(\frac{\beta^2}{\pi}\right)^{9/4} \exp\{-\frac{\beta^2}{2}\left[\sum_{i=1}^{3}(\underset{\sim}{r}_i - \frac{\underset{\sim}{R}}{2})^2\right]\} \qquad (3.2)$$

for the radial cluster wave function, the two clusters being a distance $\underset{\sim}{R}$ apart. Two parameter sets have been used:

(i) $m = 355$ MeV, $\beta^{-1} = 0.475$ fm, $a = 34.5$ MeV$\cdot$fm^{-2}, $\alpha_s = 0.97$ given by Fäßler, Fernandez, Lübeck and Shimizu[7] (FFLS) and

(ii) $m = 300$ MeV, $\beta^{-1} = 0.6$ fm, $a = 62.5$ MeV$\cdot$fm^{-2}, $\alpha_s = 1.39$ provided by Oka and Yazaki[8] (OY).

The main results are displayed in fig. 4. The colour-magnetic spin--spin term provides the dominant, repulsive contribution to $V_{NN}^{(1)}$. Both parameter sets yield the same repulsion at R = 0; they differ, however, considerably (by roughly a factor of 2.5) at R = 1 fm due to the different size parameter β. Compared to the central and spin-spin part of conventional ω, ρ meson exchange (taken from a realistic one-boson--exchange model which fits the two-nucleon data[9], this contribution yields relatively too weak repulsion in odd-parity states, which can be traced back to the different (negative) sign for the resulting spin--spin contribution, see ref.[6].

The situation is improved if the kinetic energy correction $V_{NN}^{(T)}$ is added. It yields a small attractive contribution in even-parity states and, on the other hand, a considerable repulsive contribution in odd--parity states. In fact, the FFLS set now provides a good agreement with vector-meson exchange around 1 fm in all channels, whereas the OY set is consistently too large.

This nice agreement for the FFLS set is spoiled to some extent by the remaining correction terms, namely $V_{NN}^{(P)}$ plus the contribution of the central term to $V_{NN}^{(1)}$. Whereas this contribution is negligible in even--parity states, and therefore does not destroy the agreement with

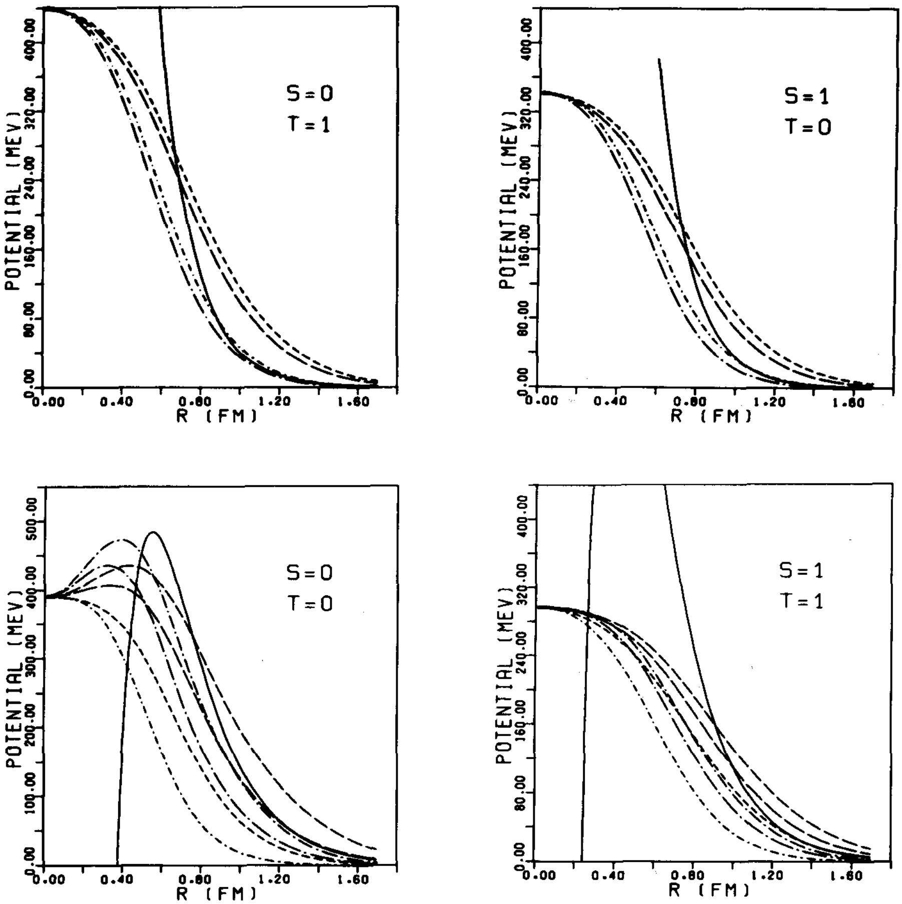

Fig. 4

V_{NN} as function of R, in the various spin-isospin channels. The solid line denotes the result provided by the central plus spin-spin part of conventional ω, ρ-meson exchange[9]. The dash-dot curves display quark--gluon-exchange results based on the FFLS parameter set[7], whereas the dashed curves originate from the OY choice[8]. The short-dashed curves denote the contribution due to the colour-magnetic term in $V_{NN}^{(1)}$, for the medium-dashed curves the kinetic-energy term $V_{NN}^{(T)}$ is added, and the long-dashed curves display the total result.

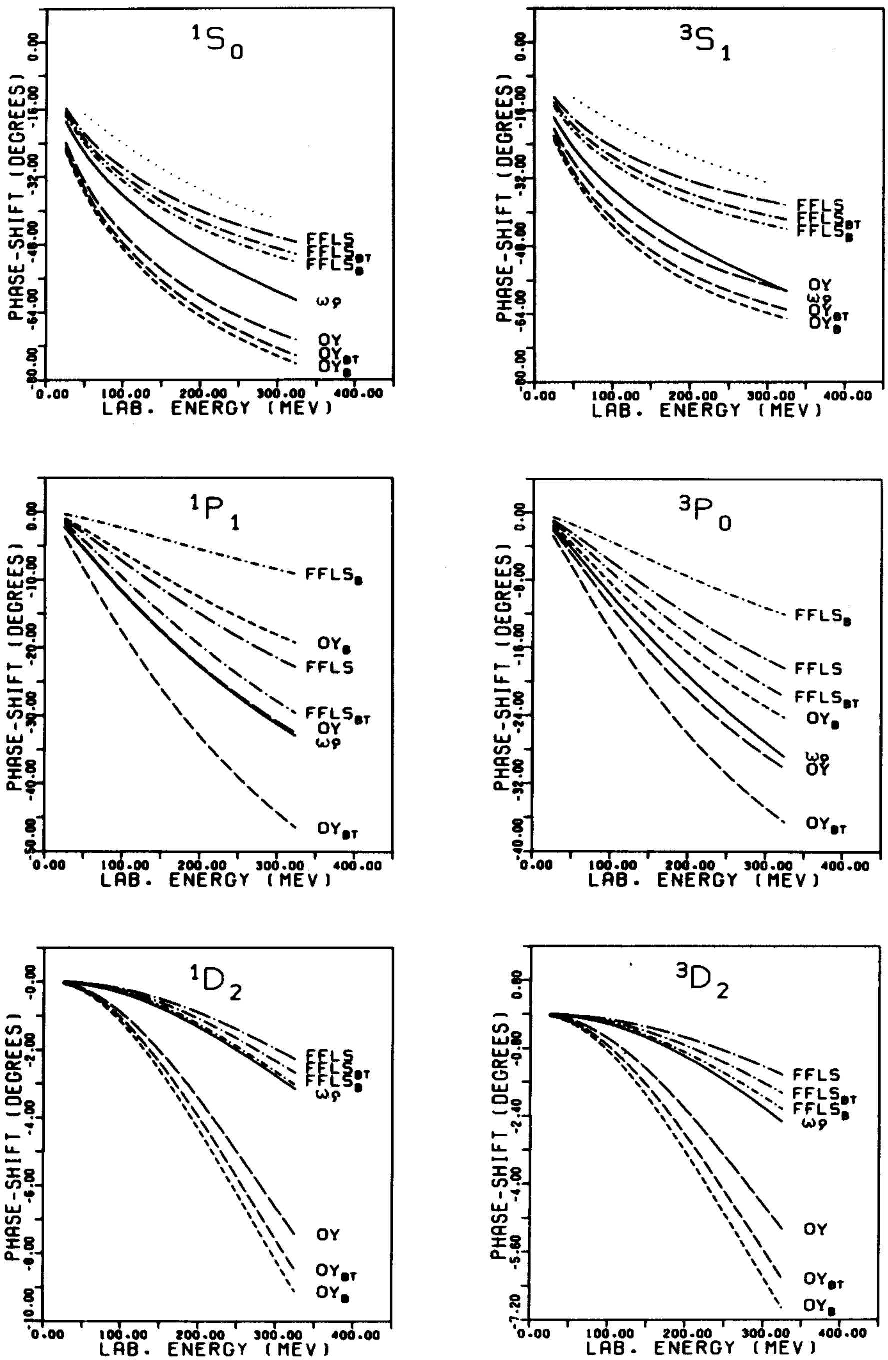

Fig. 5

(figure captions see next page)

(Fig. 5):

Nucleon-nucleon phase shifts as function of the nucleon lab energy. The solid line displays the result provided by the central plus spin-spin part of conventional ω, ρ-meson exchange[9]. The dash-dot curves display quark-gluon exchange results based on the FFLS parameter set[7], whereas the dashed curves originate from the OY choice[8]. The short-dashed curves denote the contribution due to the colour-magnetic term in $V_{NN}^{(I)}$ (B), for the medium-dashed curves the kinetic-energy term $V_{NN}^{(T)}$ is added (BT), and the long-dashed curves display the total result. The dotted curves, taken from ref.[7], result from a full resonating group calculation including all channels, based on the FFLS set.

vector-meson exchange in case of the FFLS set, it provides a strong attractive contribution in odd-parity states. Obviously, our results seem to indicate that a consistent description in all channels requires an almost complete suppression of the contribution arising from the colour-Coulomb and confining terms.

Corresponding predictions for NN scattering phase shifts, based on the effective NN interaction defined in eq. (3.1) are displayed in fig. 5. A comparison between interaction and phase shifts will clarify the role of the various contributions; especially, it will be demonstrated that the very inner part ($R < 0.5$ fm) of the NN interaction is only of minor relevance. Furthermore, our results can be compared with those from more involved resonating-group calculations. Thus the reliability of the Born-Oppenheimer scheme can be tested.

Obviously, the conclusions drawn already from the results shown for the NN interaction in fig. 4 hold also in case of the NN scattering phase shifts. Furthermore, a comparison between figs. 4,5 clearly reveals the dominant role of the region around $R = 1$ fm governing low-energy phase shifts and a correspondingly negligible role of the very inner part, especially for P- and D-waves. For example,

(i) the attractive core of $(\omega+\rho)$-meson exchange in odd-parity states (originating from the vertex form factor, see ref.[6]) is not felt since the corresponding phase shifts in $^1P_1$, $^3P_1$ remain negative;

(ii) in case of the S-wave phase shifts, there is a strong sensitivity to the choice of parameter set, in spite of the fact that both sets provide the same repulsion at $R = 0$;

(iii) in both D-wave phase shifts, $(\omega+\rho)$-exchange yields the weakest repulsion.

With a size parameter $\beta^{-1} \simeq 0.5$ fm, additional ($\Delta\Delta$ and hidden colour) channels should start to modify the present results at $R \simeq 2 \cdot \beta^{-1} = 1$fm; their effect should increase with decreasing distance. Consequently, we do not expect drastic changes for low-energy NN scattering phase shifts, even for S-waves. In fact, full resonating-group calculations based on the FFLS set[7] lower the repulsion in S-waves by only 20 %, see fig. 5. An even smaller effect is to be expected in higher partial waves although, in odd-parity states, the contribution from the central part in the quark-quark interaction might be sensitive to our approximate treatment, since it arises from a delicate interplay between various terms.

In summary, we feel that our results provide some indication for the possible existence of an intimate connection between the one-gluon--exchange mechanism and conventional vector-meson exchange providing the short-range part of the NN interaction. Concerning the intermediate-range attraction, this part could possibly be identified with (second-order) hidden-colour contributions (colour Van der Waals forces). It is known[10] that, at large distances, these terms provide an unrealistic contribution. However, realizing that one gluon cannot be exchanged between two separated hadrons, a cutoff factor should be introduced which is related to the overlap of the two interacting nucleons[11]. Note that, since no quark-interchange is involved in such contributions, they are exactly isoscalar, which agrees with the empirical situation. Finally, it has been suggested[12] that pion exchange between two interchanged quarks inside the two-cluster bag might account for the missing short-ranged OPE-contribution. Thus, the question whether simple quark-gluon-exchange diagrams can provide essential features of the NN interaction is a fascinating and challenging problem for the future. It might well be that both pictures, conventional meson exchange and explicit quark-gluon exchange, can provide an essentially equivalent description of the empirical situation.

Fruitful discussions with A. Fäßler and M. Harvey are gratefully acknowledged. Thanks are due to C. Elster for providing some numerical results and for preparing the figures.

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