

Quark degrees of freedom in the deuteron and their testing in nucleon-deuteron scattering

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Abstract. The discrepancies between theoretical predictions and experimental data for nucleon-deuteron scattering at high momentum transfers are usually attributed to the three-nucleon force effects but inclusion of $3N$ forces (of conventional type) in exact Faddeev calculations helps to improve the agreement with the data only partially. Alternatively, the short-range part of $2N$ interaction (manifesting itself in processes with large transferred momenta) may be modified by incorporating quark degrees of freedom. Such a microscopic NN -force model — the dressed bag model — was proposed by the Moscow-Tuebingen group and is based on the production of an intermediate $6q$ bag dressed by a strong σ field. It is demonstrated that taking into account the formation of an intermediate $6q$ bag leads to a noticeable enhancement of the deuteron wave function in the high-momentum region. Our preliminary calculations performed within the dressed bag model show that the suggested mechanism of the short-range NN interaction gives significant contribution to the nucleon-deuteron scattering at high momentum transfers both through $2N$ and $3N$ forces.

1. Introduction

In 1911 Rutherford discovered the atomic nucleus, which may be called *the heart of the atom*. A century has passed since then, but still we don't know exactly, what is *the heart of the nucleus*. Namely, the question arises: what forces act and what processes occur when two or more nucleons come close to each other? It is now well known that nucleons consist of quarks interacting strongly with each other, therefore at small internucleon distances (in the two-nucleon overlap region) the quark-gluon degrees of freedom should manifest themselves. How to probe the short-range NN correlations? One possible way to do this is to study the hadronic processes — e.g. nucleon-deuteron scattering — at high momentum transfers, or at large scattering angles. Investigating the structure of the nucleus by the large-angle hadron-nucleus scattering we follow Rutherford who investigated the structure of the atom by the backward scattering of α particles.

Here we concentrate on the proton-deuteron elastic scattering. As the deuteron is a loosely bound system with internal momenta $k \lesssim 0.3$ GeV/ c , the pd elastic scattering is predominantly forward, with small momentum transfers. Indeed, typical pd differential cross section (say, at the incident energy $T_p = 1$ GeV) shows a strongly pronounced forward peak and falls down very rapidly as the scattering angle (or momentum transfer) increases. This forward peak and a part of the intermediate-angle region are well understood and can be reproduced by exact (at low and moderate energies $T_p \lesssim 350$ MeV) as well as approximate (at higher energies) methods. For example, in our recent papers [1, 2] the refined version of the conventional Glauber model, which

includes the full spin structure of colliding particles and incorporates accurate NN amplitudes and deuteron wave functions, was developed and tested in pd elastic scattering at intermediate energies. The refined Glauber model seems to be as accurate as the exact Faddeev calculations for pd elastic scattering at $T_p \gtrsim 200$ MeV, and there are a number of physical reasons for this [1].

However, at large scattering angles there exist discrepancies which cannot be clearly explained by present theories. At low and moderate energies, where exact $3N$ calculations based on the solution of Faddeev equations are applicable (see, for example, [3]), it was found that the large-angle discrepancies increase with energy. The inclusion of conventional three-body forces (of Fujita-Miyazawa type) does not help remove these discrepancies at energies higher than 135 MeV [4].

At higher energies ($T_p \simeq 1$ GeV) approximate methods based on multiple-scattering theory are usually applied. From the numerous results obtained for the pd large-angle scattering in this energy region in the last decades (see, for example, [5, 6, 7]), one can conclude that there is a substantial lack in high-momentum components of the deuteron wave function (d.w.f.). Thus, the deuteron form factor used to fit the pd backward peak in Ref. [7] was shown to greatly exceed the form factor obtained from the conventional d.w.f. at large momenta. Previous attempts to obtain the missing high-momentum components of the d.w.f. (employing nucleon resonances [5] or $6q$ bag [6]) generally were *ad hoc* and not connected to the basic NN forces. So, it would be highly desirable to incorporate the non-nucleonic degrees of freedom in the $2N$ and $3N$ systems consistently, i.e. within some plausible model of nuclear forces.

2. The dressed bag model of nuclear forces: implementation in large-angle pd scattering

The dressed bag model (DBM) of nuclear forces proposed by the Moscow-Tuebingen group some time ago [8, 9] takes into account the formation of a quark bag dressed by a strong scalar field. This mechanism is assumed to be responsible for the basic NN attraction at intermediate distances.¹ The DBM is free from several inconsistencies inherent in the conventional meson-exchange picture of NN interaction.

The basic features of the DBM are as follows: (i) two-channel NN system (the second — “internal” — channel is the dressed $6q$ bag) governed by a 2×2 Hamiltonian; (ii) just a few parameters derived from microscopic quark–meson model or fitted to NN phase shifts; (iii) the same coupling constants and cut-off parameters for the $2N$ and $3N$ systems.

The new part of two-body force (due to the coupling to the internal channel) as well as the new type of three-body force naturally arise in this model. The main purpose of the present study is to estimate the qualitative effects introduced by these new $2N$ and $3N$ forces into the three-body scattering processes like pd scattering.

2.1. Two-body forces

The NN interaction in the DBM along with the conventional t -channel meson-exchange (except the σ -exchange) part contains an additional term, which is schematically shown in Fig. 1. This term represents the s -channel production of a $6q$ bag dressed by a σ field and thus gives an effective interaction in the NN channel due to the coupling to the internal (bag) channel. The respective nonlocal and energy-dependent potential can be written as a sum of separable terms in each partial wave [8]:

$$W(\mathbf{r}, \mathbf{r}', E) = \sum_{J, M, L, L'} \varphi_L^{JM}(\mathbf{r}) \lambda_{LL'}^J(E) \varphi_{L'}^{JM*}(\mathbf{r}'). \quad (1)$$

¹ For the recent experimental and theoretical indications for the importance of this mechanism see [10].

The energy-dependent coupling constants $\lambda_{LL}^J(E)$ appearing in Eq. (1) are directly calculated from the loop diagram shown in Fig. 1.

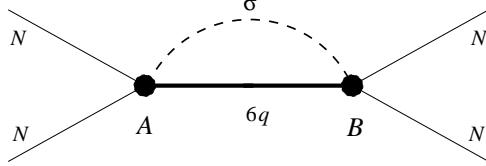


Figure 1. Effective NN interaction induced by the production of an intermediate dressed bag.

The deuteron properties as well as NN phase shifts up to 1 GeV were accurately described within the DBM [8]. However, the deuteron wave function is different somehow from the conventional one. Firstly, the d.w.f. has two components:

$$|\Psi_d\rangle = |\Psi_d^{NN}\rangle + |\Psi_d^B\rangle = \Psi_d^{NN}|NN\rangle + \Psi_d^B|B\rangle. \quad (2)$$

Here $|B\rangle$ denotes the “internal” dressed-bag ($6q + \sigma$) state appearing in the deuteron with the probability $P_B \simeq 2.5\%$ and orthogonal to the NN state, i.e. $\langle NN|B\rangle = 0$. Secondly, the “external” NN component of the d.w.f. also differs from the conventional d.w.f. in the short-range or high-momentum region due to the inclusion of the effective interaction $W(\mathbf{r}, \mathbf{r}', E)$ in the NN potential. The deuteron S - and D -wave functions (u and w) in the NN channel and also the nucleon momentum distribution in the deuteron $n_d(k) = |\Psi_d^{NN}(k)|^2$ are shown in Fig. 2 in comparison with the conventional ones, obtained from the meson-exchange CD-Bonn model. As is seen from Fig. 2(b), taking into account the 6q-bag production leads to a considerable enhancement of the nucleon distribution in the deuteron in the high-momentum region. This observation should be of importance for the large-angle pd scattering.

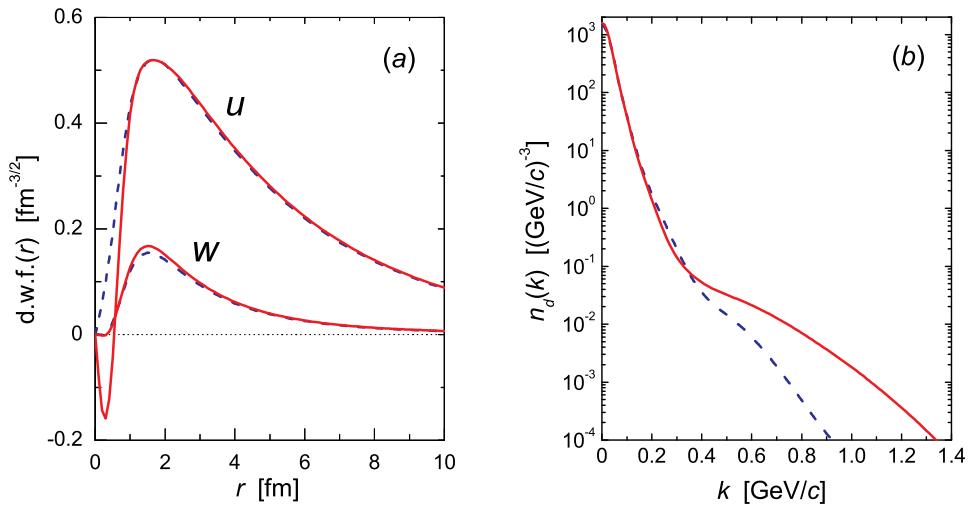


Figure 2. Deuteron wave functions (a) and nucleon momentum distributions in the deuteron (b) in two NN -force models: CD-Bonn (dashed curves) and DBM (solid curves).

In view of two-component nature of the d.w.f., the amplitude of elastic pd scattering as a function of momentum transfer \mathbf{q} may be written in the following way:

$$F^{pd}(\mathbf{q}) \equiv \langle \Psi_d | O(\mathbf{q}) | \Psi_d \rangle =$$

$$\langle \Psi_d^{NN} | O^{NN}(\mathbf{q}) | \Psi_d^{NN} \rangle + \langle \Psi_d^B | O^B(\mathbf{q}) | \Psi_d^B \rangle + 2\text{Re}(\langle \Psi_d^{NN} | O^{NN,B}(\mathbf{q}) | \Psi_d^B \rangle). \quad (3)$$

In the Eq. 3 the superscripts NN and B are related to the deuteron, and the plane waves describing the incident and outgoing protons are tacitly implied. In the lowest approximation we can neglect the interference term (the last one in the Eq. 3), that is we assume that the scattering operator $O(q)$ doesn't change the incoming channel ($NN \rightarrow B$ or vice versa). Further, the NN -channel pd amplitude $\langle \Psi_d^{NN} | O^{NN}(\mathbf{q}) | \Psi_d^{NN} \rangle$ is taken to be the sum of the direct-scattering and rearrangement amplitudes. The direct high-energy scattering gives the main contribution to the small-angle region and can be described by the refined Glauber model [1], while the rearrangement (nucleon-exchange) processes take place predominantly in the backward region. It is well known that the leading process in the backward region at rather high energies is the nucleon pick-up, which will be hereafter called ONE (one-nucleon-exchange). The ONE amplitude is taken in the present study as the first-order approximation to the rearrangement part of the NN -channel pd amplitude.

The ONE cross section is proportional to the fourth power of the d.w.f. in momentum representation, i.e. to the square of the nucleon momentum distribution in the deuteron [5]:

$$d\sigma^{ONE}/d\Omega_{c.m.} = (2\pi)^4 \left(\frac{\bar{m}}{m_N} \right)^2 (\kappa_d^2 + \Delta^2)^2 n_d^2(\Delta), \quad (4)$$

where $\Delta = p_{c.m.} (5/4 + \cos\theta_{c.m.})^{1/2}$, κ_d^2/m_N is the deuteron binding energy and \bar{m} is the reduced mass of pd system. The comparison between the ONE cross sections obtained within the DBM and the conventional CD-Bonn model is shown in Fig. 3. It is seen that the enhancement of the

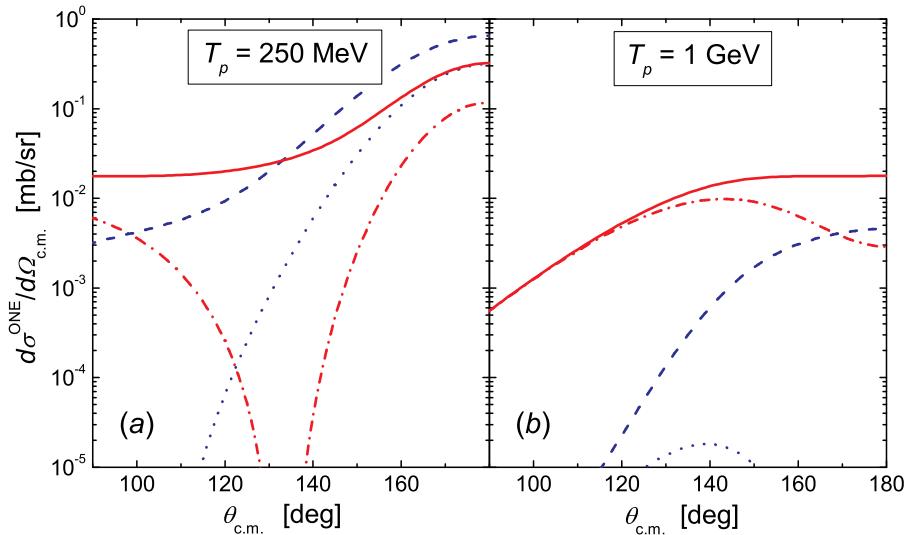


Figure 3. Differential cross sections for ONE mechanism calculated with CD-Bonn (dashed curves) and DBM (solid curves) d.w.f. at the energies $T_p = 250$ MeV (a) and 1 GeV (b). Contributions of S -wave functions only are shown by dotted (CD-Bonn) and dash-dotted (DBM) curves.

nucleon momentum distribution in the deuteron obtained within the DBM (see Fig. 2) clearly manifests itself in backward pd scattering at intermediate energies. It should be mentioned here that this is not the case for the forward pd scattering, as the predictions of the Glauber model were shown to be essentially the same for the DBM and CD-Bonn d.w.f. [2]. Since

the NN amplitudes used in the refined Glauber model are obtained from experimental data (which were described in the DBM as well as in the conventional OBE models), they should not be altered due to the DBM modification of the NN potential (see Eq. 1). Therefore, the only effect introduced by this modification of two-body forces into three-body scattering in our present simple consideration (refined Glauber model + ONE) is that of d.w.f. high-momentum components taken into account through the ONE mechanism, and this effect is shown to be quite large.

2.2. Three-body forces

The new three-body forces arising in the DBM are assumed to be the one- and two-meson exchanges between the $6q$ bag and the third nucleon [9]. They are schematically shown in Fig. 4. As the main meson field surrounding the bag is the σ field, the one-sigma exchange (OSE)

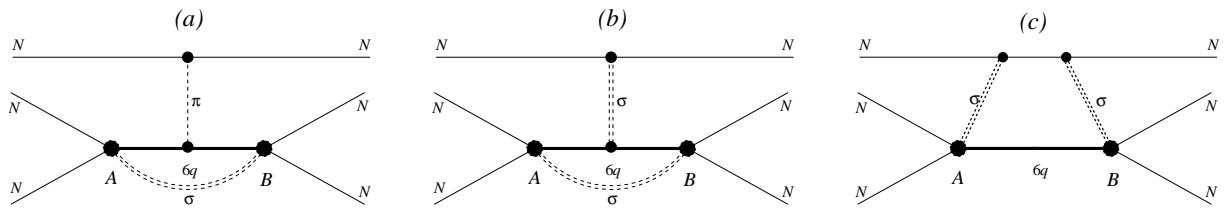


Figure 4. The graphs corresponding to three new types of three-body force.

depicted in Fig. 4(b) should dominate (for additional arguments see [9]). So, the OSE amplitude is taken in the present study to represent the “bag” (B -channel) part of the pd scattering amplitude — $\langle \Psi_d^B | O^B(\mathbf{q}) | \Psi_d^B \rangle$. The matrix element for OSE is approximately proportional to the weight P_B of the “internal” dressed-bag component of the d.w.f., because the OSE potential contains no spin dependence and we neglect the $6q$ -bag recoil. Thus, the differential cross section for the OSE process can be written in the form:

$$d\sigma^{OSE}/d\Omega_{c.m.} = P_B^2 |f^{OSE}|^2, \quad (5)$$

where the two-body OSE amplitude f^{OSE} is calculated using the potential

$$V^{OSE}(q) = \frac{-g_\sigma^2}{q^2 + m_\sigma^2}. \quad (6)$$

The coupling constant $g_\sigma^2 \equiv g_{\sigma N N} g_{\sigma 6q 6q}$ was adjusted previously using the observable properties of the $3N$ nuclei — ${}^3\text{H}$ and ${}^3\text{He}$ [9].

The predictions for pd differential cross section based on the refined Glauber model for small-angle region plus ONE mechanism for large-angle region with and without inclusion of the effective $3N$ force induced by OSE mechanism are shown in Fig. 5 together with experimental data at two incident energies $T_p = 250$ MeV and 1 GeV. The results of exact Faddeev calculations at the incident energy $T_p = 250$ MeV, based on pure $2N$ forces and with inclusion of conventional $3N$ forces, are given as a reference point (see Fig. 5(a)). It can be seen that the OSE mechanism gives noticeable contribution to the large-angle pd scattering at higher energy $T_p = 1$ GeV and at lower energy $T_p = 250$ MeV the two-body forces derived within the DBM already reproduce the large-angle behaviour of the pd cross section quite well. As for the backward direction $\theta_{c.m.} = 180^\circ$, the result of the full calculation including the OSE three-body force is in a qualitative agreement with the experimental data at both energies. The next step is to study how the results presented here will be affected by taking account of rescattering corrections to ONE, relativistic effects, other types of three-body forces, etc.

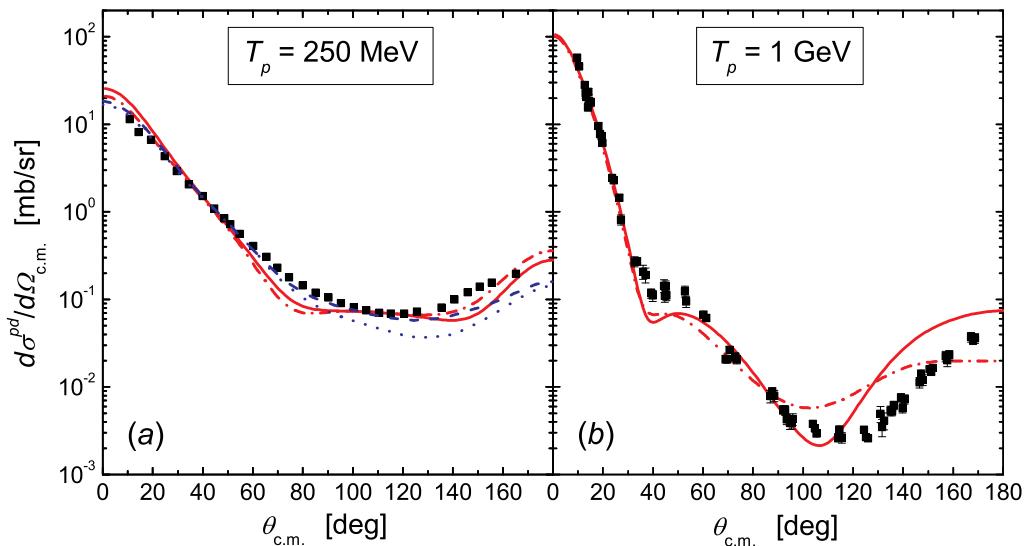


Figure 5. Differential cross sections given by the pure $2N$ forces (dash-dotted curves) — refined Glauber model plus ONE — and with inclusion of OSE-induced $3N$ force (solid curves) at the energies $T_p = 250$ MeV (a) and 1 GeV (b). In the panel (a) the results of Faddeev calculations with CD-Bonn potential (dotted curve) and with inclusion of TM'99 $3N$ force (dashed curve) are also shown. Experimental data (squares) and Faddeev results are taken from Ref. [11].

3. Summary

It is intuitively clear that quark degrees of freedom should manifest themselves at short NN distances. The pd scattering has been considered as a probe of short-range NN correlations. The pd elastic cross section at small scattering angles was shown previously to be reproduced well by the refined Glauber model at the energies $T_p \gtrsim 200$ MeV. In the large-angle region, where the present theories encounter substantial problems, the dressed bag model (DBM) has been applied, which takes into account the formation of an intermediate σ -dressed $6q$ -bag. This mechanism of the short-range NN interaction leads to the emergence of new two- and three-body forces. Our first calculations within the DBM have shown that these new forces give significant contributions to the large-angle pd scattering. It is worth emphasizing that these calculations have been carried out with *no free parameters*. More detailed calculations are in progress.

Acknowledgments

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