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Yu.N.Uzikov*

ON CONTRIBUTION OF THREE-BODY FORCES TO *Nd* INTERACTION AT INTERMEDIATE ENERGIES

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*E-mail address: uzikov@nusun.jinr.dubna.su

An existence of the three-nucleon forces (3NF) is not doubted both in the standard meson-exchange picture [1] and in the ciral perturbation theory [2]. Their strength and detail structure are still under discussion [3]. An often used model of a 3NF is the 2π exchange in the form called the Tucson-Melbourne (TM-3NF) parametrization [1] (Fig.1). At present nucleon-nucleon (NN) forces underestimate binding energies of the light nuclei [4]. The 3NF allow one to fill in part the gaps. Another signal for the 3NF gives elastic Nd scattering below 200 MeV. Recent experimental and theoretical investigations [5, 6, 7, 8, 9] show that reach set of spin observables in this process gives a real chance to study various aspects of 3NF effects. So, the measured cross section, which is underestimated at the scattering angles $\theta_{cm} = 60^\circ - 180^\circ$ by the data-equivalent modern NN forces, is excellently reproduced by three-body calculations with the TM-3NF. The deuteron analyzing power A_y^d is also well reproduced [10]. On the other hand, the nucleon analyzing power A_y^p is still under discussion [11], [12]. Furthermore, the same approach fails to explain tensor analyzing powers from the precise dp scattering data [10]. From this observation the authors of Ref. [10] conclude that there is deficiencies in the spin structure of the TM-3NF.

However, one should note that off-shell properties of NN forces contribute simultaneously with the 3NF. The problem is that these ambiguous aspects of NN forces can be studied in the 3N or many nucleon systems only (see recent discussion in Ref. [12]). A noticeable NN input dependence was observed in Refs.[10, 13]. In this connection the authors of Ref. [13] proposed to measure the zero point of the longitudinal asymmetry in the $\vec{n}\vec{d}$ total cross section in order to get more clear signal for 3NF effects. This letter is another step in that direction. Namely, to separate more definitely the NN and 3NF effects in the elastic Nd scattering one should investigate supplementary processes at almost the same kinematics but with a different relative role of the NN and 3NF. As shown here, a substantial different NN-to-3N ratio occurs in the pd-interaction with formation of the spin-singlet NN-pair in the final ${}^1S_0$ state. We propose here to study the reactions

$$p + d \to (pp) + n \tag{1}$$

and $n + d \to (nn) + p$ at large cm scattering angle of the secondary nucleon and low relative energy of two protons (pp) or neutrons (nn) $E_{NN} < 3$ MeV, when the ${}^1S_0$ state dominates. The reaction (1) was not yet investigated experimentally. Complete theoretical analysis of this reaction is possible at present at energies below the pion threshold (214 MeV) in the framework of rigorous 3N-scattering approaches [14, 15]. As shown by Faddeev calculation, at initial energies below about 200 MeV rescattering of higher order is very important. However, around 300 MeV the first two terms in the multiple scattering expansion are sufficient to describe the total nd cross section [7]. Therefore, the first Born approximation can be used as a qualitative estimation near the pion threshold. Within this approximation one cannot find an exact contribution of the 3NF. Nevertheless, we can show qualitatively that the relative role of the NN and 3NF forces differs in this reaction considerably from that in the elastic Nd scattering. First, using isospin invariance, we show that the Born 3NF amplitude (Fig.1a) of the reaction with the singlet $pn({}^1S_0)$ pair is suppressed by the factor of $\frac{1}{3}$ in respect to the 3NF amplitude with the deuteron. On the other hand, the Born term of the one nucleon exchange (ONE) mechanism (Fig.1c), related to the NN-forces, is not affected by isospin factors. Second, the ONE contribution is modified considerably due to suppression of the higher orbital momenta $l \neq 0$ in the final NN-system at low E_{NN} whereas it is not so for the 3NF. In additional, an important modification of the single scattering (SS) mechanism (Fig.1d) occurs in the reaction (1) in comparison with the $pd \to dp$.

The dynamics of the reaction (1) is discussed here by analogy with known mechanisms of the backward elastic pd-scattering [16, 17] (see Fig.1). As we show below, the ONE+SS sum dominates in the $pd \to dp$ process at energies $T_p \sim 0.2 - 0.3$ GeV. At higher energies $T_p = 0.4 - 1.0$ GeV the double pN-scattering (Fig.1e) with the Δ-excitation (Δ) gives the main contribution [16, 18]. For the NN$\rightleftharpoons \Delta$N amplitude we use here the $\pi + \rho$ exchange model [20] depicted in Fig.1b. This model describes the measured cross section of the pp$\to pn\pi^+$ reaction [19] in the Δ-region. Since the Δ mechanism is an important ingredient of the 3NF amplitude [21], we identify here the Δ contribution with the 3NF one. The Δ-isobar is considered as a stable baryon, that is appropriate below the pion production threshold.

Let us discuss the isotopic spin factors for the Born 3NF term of the $p\,d \to (np)_{s,t}\,p$ amplitude depicted in Fig.1a. The 2π exchange mechanism contains two terms corresponding to different values of the total isospin of the intermediate meson-nucleon system, $T = \frac{1}{2}$ and $\frac{3}{2}$:

$$A(p\,d \to (pn)_s\,p) = A^s_{T=1/2} + A^s_{T=3/2}, \qquad (2)$$
$$A(p\,d \to (pn)_t\,p) = A^t_{T=1/2} + A^t_{T=3/2},$$

where the spin singlet (s) and triplet (t) states of the final pn-pair correspond to the isospin $T_{pn} = 1$ and 0, respectively. The isospin structure of the amplitudes $A^{s,t}_T$ is given by

$$A^{s,t}_T(p\,d \to (pn)\,p) = (2T+1)\sqrt{2(2T_{pn}+1)}(T_{pn}0\frac{1}{2}\frac{1}{2}|\frac{1}{2}\frac{1}{2})\times$$
$$\times \left\{ \begin{array}{ccc} 1 & \frac{1}{2} & \frac{1}{2} \\ 1 & \frac{1}{2} & T \end{array} \right\} \left\{ \begin{array}{ccc} \frac{1}{2} & \frac{1}{2} & T_{pn} \\ \frac{1}{2} & \frac{1}{2} & 1 \end{array} \right\} B^{s,t}_T. \qquad (3)$$

The Clebsh-Gordan coefficients and 6j-symbols are used here in standard notations. The dynamical factor B_T in Eq. (3) does not depend on z-projections of the isotopic spins. Assuming the spatial parts of the singlet and triplet wave functions of the pn pair to be the same, i.e. $B^s_T = B^t_T$, one can find from Eq.(3) the following ratios

$$r = \frac{A^s_{T=1/2}}{A^t_{T=1/2}} = \frac{A^s_{T=3/2}}{A^t_{T=3/2}} = -\frac{1}{3}. \qquad (4)$$

After substituting Eq. (4) into Eq. (2), one finds

$$R^{iv}_I = \frac{A(p\,d \to (pn)_s\,p)}{A(p\,d \to (pn)_t\,p)} = -\frac{1}{3}. \qquad (5)$$

We stress that owing to Eq.(4) the ratio (5) does not depend on the unknown relative phase nor on the ratio of the amplitudes $A_{1/2}$ and $A_{3/2}$ of the virtual process $\pi N \to \pi N$ in Eq.(2). The result given by Eq.(5) is valid not only for the Δ-mechanism (Fig.1e), as was found in Ref. [22]. In fact, all intermediate states of the meson-nucleon system both for the isotopic spin T=3/2 and T=1/2 are taken into account in Eq.(5) including the Δ and N^*

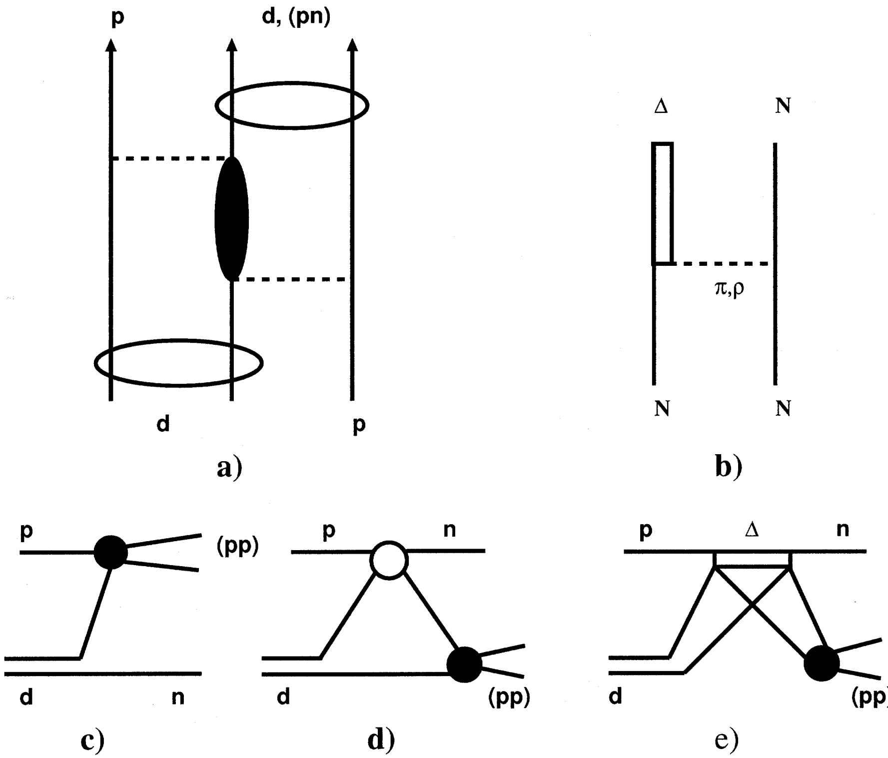

Figure 1: Mechanisms of the reaction $p + d \to (NN) + N$: $a)$ – the Born 3NF amplitude of the $pd \to (pn)p$ and $pd \to pd$ reactions, $b)$ — $\pi + \rho$ exchange for the $NN \to N\Delta$ amplitude; (c) – one nucleon exchange, (d) – single scattering, (e) – Δ-isobar excitation

poles and the πN continuum. Obviously, the relation (5) is valid also for the sum of the diagrams in Fig.1a with different combinations of the isovector mesons $(\pi\pi, \pi\rho, \rho\rho, \ldots)$, as well as for the reaction $pd \to dN^*$.

For the isoscalar meson exchange $(\omega,\ \eta,\ \eta',\ \ldots)$ we find the ratio $R_I^{is} = 1$. The same ratio is valid for the ONE mechanism, $R_I^{ONE} = 1$. It is impossible to write a definite isotopic factor for the SS-mechanism because in this case the s/t ratios are different for the isoscalar $(r = 1)$ and isovector $(r = \frac{1}{3})$ NN-amplitudes, which are mixed with an unknown relative phase in the upper vertex of the diagram in Fig.1d.

A detail formalism for the amplitude of the reaction $pd \to (NN)N$ in the framework of the ONE+SS+Δ model can be derived from the $pd \to dp$ formalism of Ref. [16, 18]. For this aim one should make the following substitution into the matrix elements

$$|\varphi_d > \to \sqrt{m}|\Psi_{\mathbf{k}}^{(-)} >, \tag{6}$$

where $|\varphi_d >$ is the deuteron final state in the $pd \to dp$ and $|\Psi_{\mathbf{k}}^{(-)} >$ is the scattering state of the final NN-system at the relative momentum $\mathbf{k}$ in the $N + d \to (NN) + N$ reaction. Since the S-wave gives the main contribution to the NN-state at $E_{NN} < 3$ MeV, one should omit the D-component of the final deuteron state $|\varphi_d >$ in the $pd \to dp$ formalism [16, 18] when making the substitution (6). Thus, one has to insert into the upper vertex of the ONE diagram (Fig.1c) the half-off-shell amplitude of pn-scattering in the $^1S_0$ state, $t_s(q, k)$. This amplitude, as a function of the off-shell momentum q, is very close in its shape to the deuteron S-wave function in momentum space, $u(q)$, and has a node at the point $q \sim 0.4$GeV/c. The node is caused by the short-range repulsion in the NN potential. A similar node available in the wave function $u(q)$ can be connected to the null of the deuteron charge formfactor $G_C(Q)$ at the transferred momentum $Q \sim 4.5$ fm^{-1} [23]. The node of $u(q)$ was not yet observed directly in any reactions with the deuteron due to large contribution of the deuteron D-state. An important feature of the reaction (1) is a possibility to display the node of the amplitude $t_s(q, k)$ directly in the cross section at $T_p = 600 - 700$ MeV and $\theta_{cm} = 180^o$ [24, 25]. At initial energies 100-300 MeV this node makes the ONE contribution vanishing at $\theta_{cm} = 100^\circ - 130^\circ$.

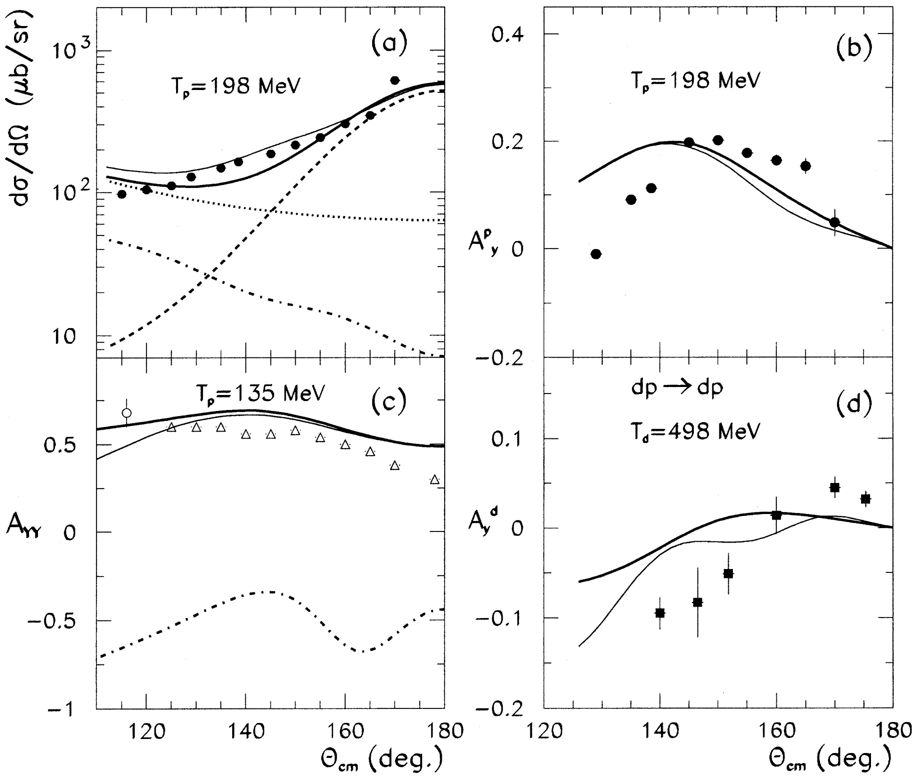

Figure 2: The cm cross section (a) and analyzing powers A_y^p (b), $A_y^d(d)$, $A_{yy}^d(c)$ in the pd-elastic scattering in backward hemisphere at different initial energies of the proton T_p and the deuteron T_d $(T_p = \frac{1}{2}T_d)$. The results of calculations with the different mechanisms are compared with the experimental data from Refs. [26](•), [27] (filled squares), and [10] (open triangles and circles): ONE (dashed line), SS (dotted), Δ (dashed-dotted), ONE+SS (full thick), ONE+SS+Δ (full thin)

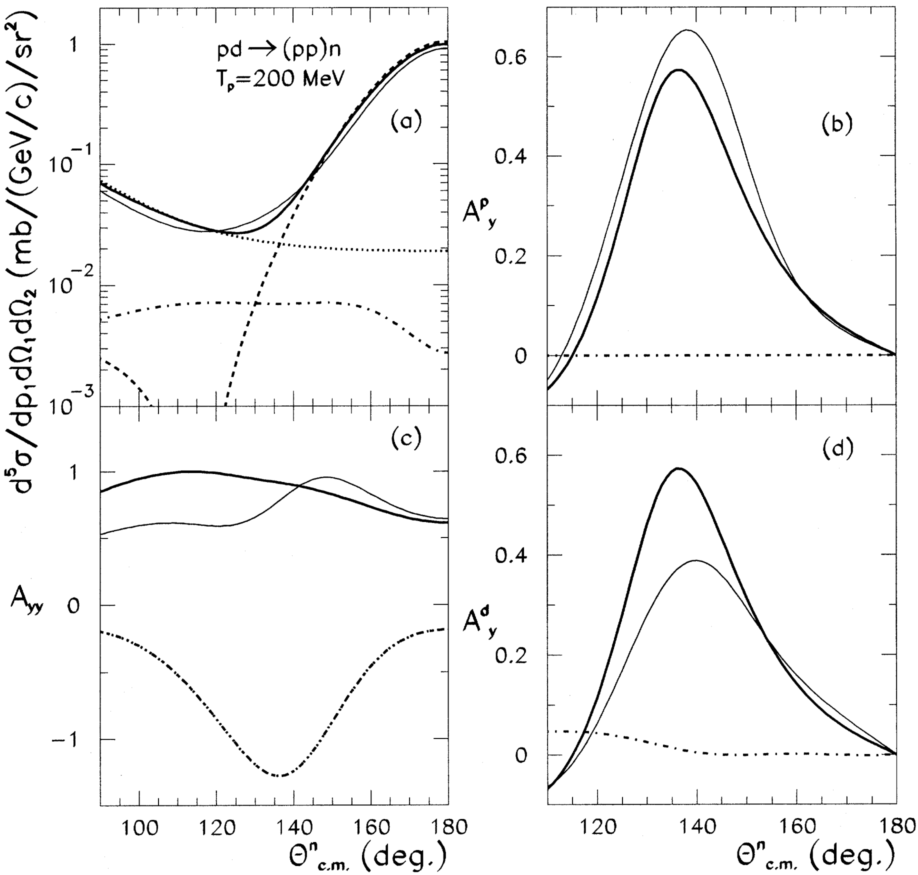

Figure 3: The same as in Fig.2, but for the reaction $p + d \to (pp)_s + n$ at $T_p = 200$ MeV and relative energy of two protons $E_{pp} = 3$ MeV versus the neutron scattering angle θ^n_{cm}

The results of our calculations performed within the ONE+SS+Δ model with the Paris NN-potential are shown in Fig.2 for the $pd \to dp$ process and in Fig.3 for the reaction (1). The model describes rather well the $pd \to dp$ cross section at $T_p = 150 - 250$ MeV and $\theta_{cm} > 120°$. The Δ(≡3NF) contribution strongly depends on the cutoff parameters $\Lambda_{\pi,\rho}$ in the NN$\rightleftharpoons$ ΔN amplitude. We use here the values $\Lambda_\pi = 0.6$ GeV and $\Lambda_\rho = 0.7$ GeV obtained from the fit the data on $pp \to pn\pi^+$ and $pd \to dp$ [20, 18]. The sum ONE+SS underestimates the cross section at $\theta_{cm} = 110° - 130°$, but this discrepancy is eliminated by adding the Δ-contribution (Fig.2a), as was observed in Refs.[6, 21]. The calculated analyzing powers A_y^p, A_y^d, and A_{yy} are in only qualitative agreement with the data (Fig.2b-d).

In contrast to the $pd \to dp$ process, the influence of the Δ mechanism in the reaction (1) is rather weak in the cross section, but more pronounced in the analyzing powers (Fig.3). At the minimum of the cross section, $\theta_{cm}^n = 120° - 140°$, the role of 3NF increases due to i) vanishing of the ONE amplitude and ii) rather fast decreasing of the SS contribution (Fig.3a). Outside of this region the Δ contribution to the reaction (1) is smaller than in the elastic pd scattering owing to the isospin relations. Note, within the ONE+SS approximation the behaviour of the vector analyzing powers A_y^p and A_y^d is considerably different in the reaction (1) as compared to the $pd \to dp$ process (Figs. 3b,d). The reason is a modified structure of the SS-mechanism. Indeed, only the pn-scattering at small angle contributes to the upper vertex of the SS mechanism in the reaction (1) [24]. On the contrary, both the charge exchange process $pn \to np$ and the pp elastic scattering at small angles contribute to the $pd \to dp$ process [16]. The Δ mechanism taken into account in addition to the ONE+SS sum, changes the analyzing powers noticeably (Fig.3c,d)

In conclusion, the ONE+SS+Δ model allows one to understand qualitatively the main features of the $pd \to dp$ observables at $T_p \sim 200$ MeV. Within this model we found that the relative contribution of the 3NF in the reaction $N + d \to (NN)(^1S_0) + N$ differs considerably from the elastic pd scattering. A sizable modification of the analyzing powers is expected in the reaction (1) in comparison with the $pd \to dp$, in particular, due to the 3NF effects. Future experimental study of the reaction (1) near the pion threshold and rigorous three-body calculations, complementing the process $pd \to dp$, can give more insight about the 3NF.

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Узиков Ю.Н. E4-2001-237

О вкладе трехчастичных сил в *Nd*-взаимодействие при промежуточных энергиях

Имеющиеся данные об упругом рассеянии нуклонов на большие углы на дейтроне $Nd \to dN$ ниже пионного порога демонстрируют проявление трехнуклонных сил. Существует проблема отделения вклада возможных тонких аспектов этих сил от внеэнергетических эффектов в двухнуклонном *NN*-потенциале. На базе основных механизмов процесса $Nd \to dN$ качественно показано, что в квазидвухчастичной реакции $N + d \to (NN) + N$ с конечной спин-синглетной *NN*-парой в *S*-состоянии относительный вклад трехчастичных сил значительно отличается от упругого канала. Это дает новые критерии для изучения рассматриваемой проблемы.

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Uzikov Yu.N. E4-2001-237

On Contribution of Three-Body Forces to *Nd* Interaction at Intermediate Energies

Available data on large-angle nucleon-deuteron elastic scattering $Nd \to dN$ below the pion threshold give a signal for three-body forces. There is a problem of separation of possible subtle aspects of these forces from off-shell effects in two-nucleon potentials. By considering the main mechanisms of the process $Nd \to dN$, we show qualitatively that in the quasi-binary reaction $N + d \to (NN) + N$ with the final spin singlet *NN*-pair in the *S*-state the relative contribution of the 3*N* forces differs substantially from the elastic channel. It gives a new testing ground for the problem in question.

The investigation has been performed at the Dzhelepov Laboratory of Nuclear Problems, JINR.

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