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Relativistic effects in proton-induced deuteron break-up at intermediate energies with forward emission of a fast proton pair

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Abstract. Recent data of the reaction $pd \to (pp)n$ with a fast forward pp pair with small excitation energy is analyzed within a covariant approach based on the Bethe-Salpeter formalism. Relativistic effects in cross-section are extracted and found to be large. It is demonstrated that the node of the non-relativistic amplitude is shifted and masked by relativistic effects from Lorentz boost and the negative-energy P components in the $^1S_0$ Bethe-Salpeter amplitude of the pp pair.

PACS. 13.75.Cs Nucleon-nucleon interactions (including antinucleons, deuterons, etc.) – 25.10.+s Nuclear reactions involving few-nucleon systems

1 Introduction

The investigation of hadronic processes at high energies provides a refinement of information about strong interaction at short distances. Nowadays, large research programs of experimental studies of processes with polarized particles are in progress. Important are setups with deuteron targets or beams [1–3], since the deuteron serves as a unique source of information on neutron properties at high transferred momenta, the knowledge of which allows, *e.g.*, to check a number of QCD predictions and sum rules. Of interest is furthermore the study of nucleon resonances, effective meson-nucleon models, NN potentials, etc. In this line is the investigation of the deuteron break-up reaction with a fast pp pair at low excitation energy, proposed in [3] and with first results reported in [4].

One motivation for the experiment [4] was the possibility to investigate the off-mass-shell effects in NN interactions. As predicted in [3–5], at a certain initial energy of the beam protons, the cross-section should exhibit a deep minimum, corresponding to the node of the non-relativistic $^1S_0$ wave function of the two outgoing protons, provided the non-relativistic picture holds and off-mass-shell effects can be neglected. The recent data [4] exhibits, however, a completely different behavior: the cross-section is smoothly decreasing; there is no sign of a pronounced minimum. It is found within the usual non-relativistic framework that accounting for corrections beyond the one-nucleon-exchange mechanism and employing the most recent NN potentials like CD Bonn [6] instead of Reid soft-core and Paris ones improve the agreement with the data [7].

The considered reaction with the production of a pp pair in an $^1S_0$ state is particularly interesting since here several additional mechanisms beyond the one-nucleon exchange are expected to be of sub-leading order. For instance, because of isospin invariance, the contribution of Δ isobars is much smaller than in, *e.g.*, the kinematically similar reaction of elastic pd scattering [5,8,9].

It is clear that a purely non-relativistic treatment of this process can become inadequate. There are two basic reasons: i) the high virtuality of the proton in the deuteron at the considered kinematics, ii) the large total momentum of the final pp pair. Consequently, other approaches which take into account relativistic effects and the off-mass-shellness of the interacting nucleons are desired. The Bethe-Salpeter (BS) formalism can serve as an appropriate approach to the problem, because the off-mass-shellness of the nucleons is an intrinsic feature of the BS equation. Moreover, the solution of the BS equation, being manifestly covariant, incorporates genuine relativistic effects (Lorenz boosts, negative-energy components, etc.).

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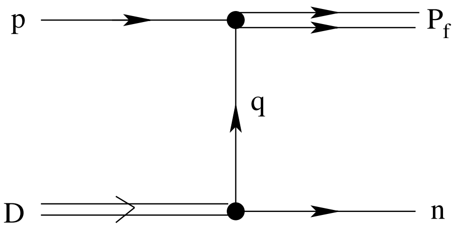

Fig. 1. Kinematics of the process (1).

In the present paper we use the BS approach to analyze the data [4] on deuteron break-up with the emission of a fast forward pp pair [10]. The main goal of this paper is to extract the relativistic effects and investigate their influence on the observables. The calculation is based on our solution of the BS equation for the deuteron with a realistic one-boson-exchange kernel [11]. The final-state interaction of the two protons is treated also within the BS formalism, by solving the BS equation for the t-matrix within the one-iteration approximation [8,12]. In doing so, a big deal of off-mass-shell effects and relativistic corrections are taken into account already within the relativistic spectator mechanism. In particular, as shown in [8,12], an account of the P-waves within the BS formalism exactly corresponds to non-relativistic calculations of meson-exchange current corrections from the $N\bar{N}$ pair production.

2 Kinematics

In this paper we follow the basic ideas from [13]. Let us consider the process

$$p + d = (p_1 p_2)(0^\circ) + n(180^\circ) \qquad (1)$$

at low excitation energy of the pair ($E_x \sim 0$–3 MeV) and intermediate initial kinetic energies $T_p \sim 0.6$–2.0 GeV corresponding to the conditions at the Cooler Synchrotron COSY in the experiment [3,4]. At such low values of E_x, the main contribution to the final state of the pp pair in the continuum comes from the $^1S_0$ configuration. In the one-nucleon-exchange approximation this reaction can be represented by the diagram depicted in fig. 1, where the following notation is adopted: $p = (E_p, \mathbf{p})$ and $n = (E_n, \mathbf{n})$ are the four-momenta of the incoming (beam) proton and outgoing (not registered) neutron, P_f is the total four-momentum of the pp pair, which is the sum of the corresponding four-momenta of the detected protons, $p_1 = (E_1, \mathbf{p}_1)$, $p_2 = (E_2, \mathbf{p}_2)$. The invariant mass of the pp pair is $M_{pp}^2 = P_f^2 = (2m + E_x)^2$, where m stands for the nucleon mass and E_x is the excitation energy. Our calculations are performed in the laboratory system where the deuteron is at rest. For specific purposes, the center of mass of the pair will be considered as well, where all relevant quantities are superscripted with asterisks.

A peculiarity of the process (1) is that the transferred momentum from the initial proton to the second proton in the pair is rather high. Moreover, from the kinematics one finds that the momentum of the neutron is also high enough ($|\mathbf{n}| \sim 0.3$–0.5 GeV/c), which implies that, since the outgoing neutron is on-mass-shell, the proton inside the deuteron was essentially off-mass-shell before the interaction. Correspondingly, it becomes clear that the process of NN interaction in the upper part of the diagram is more involved than an elastic interaction. For instance, let us consider a typical kinematical situation, say $|\mathbf{p}| = 1.22$ GeV/c, $\theta_1' \sim 4^\circ$, excitation energy $E_x = 3$ MeV and $|\mathbf{p}_1| = 0.765$ GeV/c. This means that the neutron momentum is $|\mathbf{n}| \simeq 0.5$ GeV/c, *i.e.*, the four-momentum of the off-mass-shell proton was $q = (M_d - E_n, -\mathbf{n})$. Now, if one supposes that in the upper vertex an elastic process of two on-mass-shell protons happens, then only one kinematical quantity would be necessary to describe the process, *e.g.*, at given $|\mathbf{p}_1| = 0.765$ GeV/c the scattering angle would be $\sim 28^\circ$ in the elastic kinematics (instead of 4° in the full reaction); or at given scattering angle 4°, the momentum of the elastically scattered proton would correspond to $|\mathbf{p}_1| = 1.21$ GeV/c ($|\mathbf{p}_2| = 0.334$ GeV/c) instead of the detected momentum $|\mathbf{p}_1| \simeq |\mathbf{p}_2| \simeq 0.765$ GeV/c. This simple example evidences the quite complicate nature of the NN interaction in the upper part of the diagram. One can consider the upper vertex of the diagram in fig. 1 as consisting of at least two steps: i) an inelastic process which puts the target nucleon on-mass-shell, and ii) an elastic interaction in the pp pair in the $^1S_0$ final state. Since a large amount of the transferred energy is needed to locate the second proton on-mass-shell, the relativistic corrections may play a crucial role here. Within the BS approach the off-shell effects are governed by some extra components of the BS amplitude usually called P-waves, and their contributions to the observables can be identified as purely relativistic corrections (see also [8]).

Another important feature of the process (1) is that the final pp pair has a large total momentum $|\mathbf{P}_f|$. It is easy to find from the kinematics that for $T_p \sim 3$ GeV one has $|\mathbf{P}_f| \sim 4.5$ GeV/c. For such a high values of the total momentum it becomes almost evident that the final state of pp pair cannot longer be described like in the rest system, without Lorentz boost. The BS approach is fully covariant, and in our further considerations we will point out the effects of Lorentz boost explicitly. The detailed analysis of the boost effects for the kinematically similar process of elastic backward $pd \to dp$ scattering can be found in [8].

3 Cross-section and matrix element

The invariant cross-section of the reaction (1) reads

$$\mathrm{d}^6\sigma = \frac{1}{(4\pi)^5\ \lambda(p,d)} |M_{fi}|^2 \frac{\mathrm{d}\mathbf{p}_1\ \mathrm{d}\mathbf{p}_2}{E_1 E_2} \times \delta\left(E_0 + E_d - E_1 - E_2 - E_n\right), \qquad (2)$$

where $\lambda(p,d)$ is the flux factor, and M_{fi} the invariant amplitude; the statistical factor 1/2 due to two identical particles (protons) in the final state has been already included. The matrix element corresponding to the relativistic one-nucleon exchange depicted in fig. 1 in the BS approach has the form

$$M_{fi} = \bar{u}(s,\mathbf{n})(\hat{n}-m)\Psi_d(n) \times \left[(\hat{p}_2+m)\overline{\Psi}_{^1S_0}(p)(\hat{p}_1-m)u(r,\mathbf{p})\right], \quad (3)$$

where $u(r,\mathbf{p})$ ($\bar{u}(s,\mathbf{n})$) stands for the Dirac spinor of the incident proton (outgoing neutron) with the spin projection r (s) and momentum $\mathbf{p}$ ($\mathbf{n}$), $\Psi_{d(^1S_0)}$ denotes the BS amplitudes of the deuteron (pp pair in the continuum). These amplitudes are considered as usual 4×4 matrices in the spinor space. They can be decomposed over a complete set of matrices, and the coefficients of such a decomposition are known as the partial BS amplitudes. There are eight independent partial amplitudes for the deuteron and four such amplitudes for the $^1S_0$ state. Their specific form depends on the chosen matrix representation. In the present paper we choose the spin angular basis in the ρ spin representation to obtain the partial decomposition of the deuteron BS amplitude Ψ_d in the laboratory system, where deuteron is at rest (for details see [8]). For the final $^1S_0$ state within the ρ spin classification the BS amplitude in the center of mass of the NN pair is represented by four partial amplitudes $^1S_0^{++}$, $^1S_0^{--}$, $^3P_0^{+-}$ and $^3P_0^{-+}$ [12], which, for the sake of brevity, in what follows are denoted as $g_1,\ldots,g_4$ [14]. In order to take into account the Lorenz boost transformation to the laboratory system, it is necessary to use the $^1S_0$ amplitude in its covariant form:

$$\sqrt{4\pi}\,\overline{\Psi}_{^1S_0}(p) = -h_1\gamma_5 - h_2\frac{1}{m}(\gamma_5\hat{p}_1+\hat{p}_2\gamma_5) - h_3\left(\gamma_5\frac{\hat{p}_1-m}{m} - \frac{\hat{p}_2+m}{m}\gamma_5\right) - h_4\frac{\hat{p}_2+m}{m}\gamma_5\frac{\hat{p}_1-m}{m}, \quad (4)$$

where $p_{1,2} = P_f/2 \pm p$, and p is the relative momentum. The four Lorenz-invariant functions $h_i \equiv h_i(P_f\cdot p, p^2)$ are linear combinations of the amplitudes g_i, $i=1,\ldots,4$ [12]. Now it is sufficient to express the amplitude (3) in terms of deuteron partial components and (4),

$$M_{fi} = (-1)^{\frac{1}{2}-r}\,\mathcal{K}(^1S_0)\frac{1}{\sqrt{8\pi}(M_d-2E_n)} \times \left\{\sqrt{2}C^{1\mathcal{M}}_{\frac{1}{2}s\frac{1}{2}-r}\left(G_S - \frac{G_D}{\sqrt{2}}\right) + 3\delta_{\mathcal{M},0}\delta_{s,r}\frac{G_D}{\sqrt{2}}\right\}. \quad (5)$$

Here the contribution $\mathcal{K}(^1S_0)$ from the upper part of the diagram in fig. 1 is

$$\mathcal{K}(^1S_0) = \sqrt{\frac{E_p+m}{E_n+m}}\left[h_1\left(E_n+m-\frac{|\mathbf{n}||\mathbf{p}|}{E_p+m}\right) - h_3\frac{M_d-2E_n}{m}\left(E_n+m+\frac{|\mathbf{n}||\mathbf{p}|}{E_p+m}\right)\right]. \quad (6)$$

$G_{S,D}$ denote the BS vertices of the deuteron, h_1, h_3 are the non-vanishing invariant partial components from (4). The relation of the amplitudes h_i ($i=1\ldots 4$) to the partial solutions of the BS equation in the NN center of mass, g_i, $i=1,\ldots,4$ has a cumbersome form and can be found, *e.g.*, in [12]. In what follows we do not discuss the contribution of the g_2 ($^1S^{--}$) and g_4 ($^3P_0^{-+}$) components, which in our case turn out to vanish exactly, keeping only the g_1 ($^1S^{++}$) component as the main one and the P component or P-wave g_3 ($^3P_0^{+-}$) as the one providing purely relativistic correction. Let us note again that, accounting for Lorentz-boost effects is achieved by using covariant representation (4) of the BS amplitude (cf. [8]).

It is easy to check that for unpolarized particles the cross-section factorizes in two independent parts, *i.e.*,

$$\frac{1}{6}\sum_{s,r,\mathcal{M}}|M_{fi}|^2 \simeq \left|\mathcal{K}(^1S_0)\right|^2\ \left(u_S(\mathbf{n})^2 + u_D(\mathbf{n})^2\right), \quad (7)$$

as it should be within the spectator mechanism with $^1S_0$ ($L_f=0$) in the final state (see also the discussion in [15]). In eq. (7) u_S and u_D are the BS deuteron S- and D-wave [8],

$$u_{S,D} \equiv \frac{G_{S,D}}{4\pi\sqrt{2M_d}(M_d-2E)}. \quad (8)$$

In our numerical calculations we use the deuteron BS amplitude from [11]. This solution has been obtained with a realistic one-boson-exchange kernel with parameters adjusted so as to fit the known characteristics of the NN system, *e.g.*, phase shifts, static properties of the deuteron, etc. (see [16,17] for details). It can be shown that within the spectator mechanism the BS amplitude enters into the cross-section as a combination of the square of its partial amplitudes known as the relativistic momentum distribution of the deuteron within the BS formalism [18] (see also eq. (7)). Our investigation [18,17] of this quantity persuades that at values of intrinsic momenta typical for the reaction (1) ($|\mathbf{n}| \sim 0.4$ GeV/c) the corrections from the negative P-waves can safely be disregarded and, as in the non-relativistic limit, one needs to consider only the S and D components. Moreover, since in this interval ($|\mathbf{n}| \sim 0.2$–0.5 GeV/c) the S component of the deuteron BS vertex has a node (see fig. 2) the main contribution from the lower part of the diagram fig. 1 comes from the deuteron D-wave only.

For the $^1S_0$ state in the continuum one should solve the inhomogeneous BS equation for the functions g_i, $i=1,\ldots,4$ in the NN center of mass to obtain the invariant amplitudes $h_{1,3}$. The partial "++" components of the BS vertices in the NN center of mass, for both the bound and the scattering states, have a direct analogue with the corresponding non-relativistic wave functions. This analogy can be understood from the formula (8): it can be shown [17] that at low intrinsic relative momenta the BS wave functions (8) basically coincide with non-relativistic ones like, *e.g.*, Bonn or Paris wave functions. Hence, due to the low excitation energy of the pp pair, in expressing $h_{1,3}$ via the partial amplitudes at rest one may safely replace the "++" vertex by its non-relativistic analogue. Relativistic effects are then included in boosting the $^1S_0^{++}$ component to the deuteron's center-of-mass system and also by taking into account the contributions of the P components in $h_{1,3}$. To find the P-waves we solve the BS

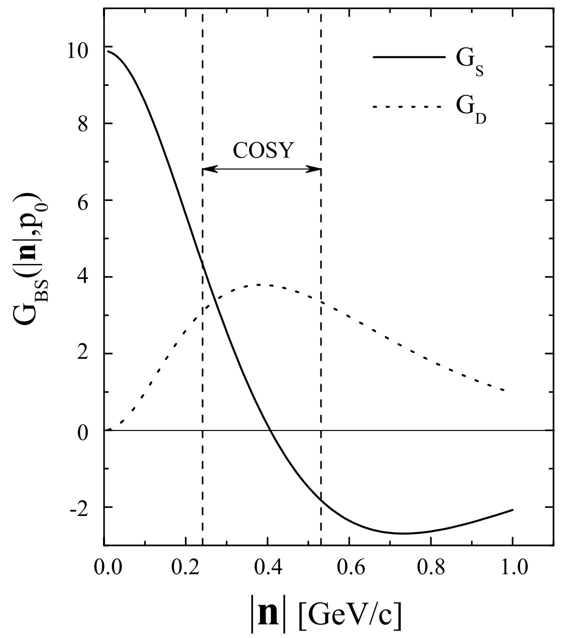

Fig. 2. The BS vertices $G_S(|\mathbf{n}|, p_0)$ (solid curve) and $G_D(|\mathbf{n}|, p_0)$ (dotted curve) as functions of the neutron 3-momentum $|\mathbf{n}|$. The relative energy is $p_0 = M_d/2 - E(\mathbf{n})$. The two dashed vertical lines show the range of the neutron momentum reached at COSY for the reaction (1).

equation for the pair in its center of mass within the one-iteration approximation [8,19], with the trial function as the exact solution for the t-matrix within a separable potential [20]. When seeking numerical solution for the BS amplitude, one can solve the BS equation by the iteration method with arbitrary trial functions. Our experience shows that, as soon as the trial function is close to the realistic solution, only few iterations are needed. Hence, if the exact non-relativistic solution is taken as a trial function, then one or two iterations are sufficient to obtain the solution in the whole kinematical region. As shown in [12], the one-iteration approximation (OIA) provides us with a very good result.

The inhomogeneous BS equation for the NN system is given and discussed in details in [19]. Here we should keep in mind that the partial components g_i $(i = 1 \dots 4)$ are already the "connected amplitudes", *i.e.*, amplitudes without the terms corresponding to free scattering. We obtain for the P-waves

$$g_3(k) = i\, g^2_{\pi NN} \left[\frac{M_{pp}}{\sqrt{\pi}} V_{31}(k, p^*) - i \int_0^\infty \frac{\mathrm{d}p\, p^2}{(2\pi)^3} V_{31}(k,p) \frac{g_1(p)}{M_{pp} - 2\,E_p + i\epsilon} \right], \quad (9)$$

where V_{31} is the corresponding partial kernel, and p^* denotes the relative momentum of the pp pair in its center of mass. Equation (9) has been obtained from the BS equation given in [19] and in its present form it does not contain any cut-off (vertex) parameter. However, in finding numerical solutions one usually introduces phenomenological vertex dipole form factors, which, besides assuring a good convergence, also simulate contributions from heavier mesons in the exchange kernel. Evidently, their role is insignificant at low exchanged momenta, but increases with increasing momentum. Correspondingly, in our case for values of the momentum near the node of the main $(++)$ $^1S_0$ component, one can neglect the vertex form factors and obtains

$$V_{31}(|\mathbf{k}|, |\mathbf{p}|, \mu^2_\pi) = \frac{\pi m}{|\mathbf{p}||\mathbf{k}| E_{\mathbf{p}} E_{\mathbf{k}}} \left\{ |\mathbf{p}| Q_1(y) - |\mathbf{k}| Q_0(y) \right\} \quad (10)$$

with $Q_L(y)$ as Legendre function with the argument $y = (|\mathbf{p}|^2 + |\mathbf{k}|^2 + \mu^2_\pi - k^2_0)/(2|\mathbf{p}||\mathbf{k}|)$ [19,12]. In eq. (10) the square of the meson mass μ^2_π in the argument of the partial kernel indicates that the vertex πNN form factor has been neglected and the meson propagator was taken in the usual form, $1/(k^2 - \mu^2_\pi)$. Accounting for the vertex form factors leads to a renormalization of the coupling constant,

$$g_{\pi NN} \longrightarrow g_{\pi NN} \frac{\mu^2_\pi - \Lambda^2}{k^2 - \Lambda^2}, \quad (11)$$

which is equivalent to the replacement of the meson propagator

$$\frac{1}{k^2 - \mu^2_\pi} \longrightarrow \frac{1}{k^2 - \mu^2_\pi} \left(\frac{\mu^2_\pi - \Lambda^2}{k^2 - \Lambda^2} \right)^2. \quad (12)$$

Then, for the "renormalized" partial kernel, one obtains

$$\mathcal{V}_{31}(k,p) = V_{31}(k,p,\mu^2_\pi) - V_{31}(k,p,\Lambda^2) + (\Lambda^2 - \mu^2_\pi) \frac{\partial V_{31}(k,p,\Lambda^2)}{\partial \Lambda^2}, \quad (13)$$

where the cutoff parameter $\Lambda = 1.29$ GeV is taken from [11], and $V_{31}(k,p,\Lambda^2)$ means the partial kernel (10) with $\mu^2_\pi \to \Lambda^2$.

In the first iteration the trial function $g_1(k)$ is expressed via the non-relativistic t-matrix [20],

$$g_1(k) = i\,(4\pi)^{5/2} \frac{m}{2}\, t_{\mathrm{NR}}(k, p^*), \quad (14)$$

where the normalization of t_{NR} corresponds to $t_{\mathrm{NR}}(p^*, p^*) = -\frac{2}{\pi m p^*} \mathrm{e}^{i\delta_0} \sin\delta_0$, with δ_0 as the experimentally known phase shift of the elastic pp scattering in the $^1S_0$ state. By using the Sokhotsky-Weierstrass formula for the Cauchy-type integrals, one finally obtains

$$g_3(k) = \frac{i g^2_{\pi NN}}{\sqrt{\pi}} \left[M_{pp} \mathcal{V}_{31}(k,p^*) \left\{ 1 - \frac{i\pi m p^*}{2} t_{\mathrm{NR}}(p^*,p^*) \right\} + m\mathcal{P} \int_0^\infty \mathrm{d}p p^2 \mathcal{V}_{31}(k,p) \frac{t_{\mathrm{NR}}(p,p^*)}{E_{p^*} - E_p} \right]. \quad (15)$$

In fig. 3 results of numerical calculations of the energy dependence of the $^1S_0$ phase shifts within the OIA are presented. It is seen that the adopted OIA assures a good description of the experimental data in a large interval of excitation energies of the pp pair. This agreement is a prerequisite for the following analysis.

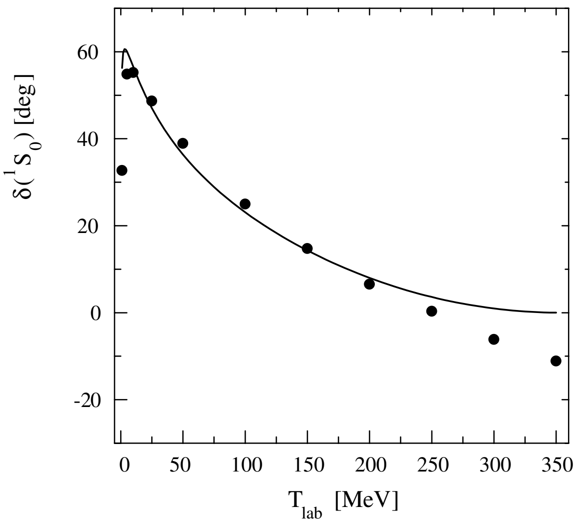

Fig. 3. The energy dependence of the $^1S_0$ *pp* phase shift computed within the BS formalism. Experimental data are from [21].

4 Numerical results and discussion

In figs. 4 and 5 we present results of numerical calculations of the five-fold cross-section $\mathrm{d}\sigma/\mathrm{d}\Omega_1\mathrm{d}\Omega_2\mathrm{d}|\mathbf{p}_1|$ and the two-fold cross-section $\mathrm{d}\sigma/\mathrm{d}\Omega_n$ (with Ω_n as the solid angle of the momentum of the neutron in the center of mass of the reaction), integrated over the excitation energy in a range $E_x = 0$–3 MeV. The calculations have been performed with our numerical solution for the deuteron BS amplitude with S and D partial components (inclusion of the P components in the deuteron amplitude leads to negligibly small corrections). The left panels in figs. 4 and 5 illustrate different contributions to the corresponding cross-section from the upper part of the diagram, fig. 1, with the lower part computed with the full deuteron (S and D components) BS wave function. The dotted curves (left panels) are results of non-relativistic calculations, while the dashed curves include pure Lorentz boost effects, *i.e.*, relativistic calculations with including the $^1S_0^{++}$ component only. It is clearly seen that the boost corrections are fairly visible: they cause a significant shift of the minimum of the cross-section. The agreement with data [4] at low initial energies becomes better; however, the cross-section is still too small at large values of T_p, see fig. 5. The thick and thin solid curves in fig. 4 depict results of our relativistic calculations. The non-relativistic results are qualitatively abandoned: the minimum due to the node of the wave function is completely hidden and the slope of the cross-section at large values of T_p is changed. Indeed, fig. 5 reveals that an account of only "++" components is not sufficient to describe the data [4]. However, a reasonable description is achieved by taking into account all the relativistic effects, including the contribution of the negative-energy P-waves, see thick and thin solid curves. With respect to the discussion in [7], the perfect agreement of our calculation without the form factor [13] (see thin curve) and the data [4] must be considered as accidental. As seen in fig. 5, the form factor pulls down the cross-section somewhat below the data points, but it is still within the error bars (we also may consider the thin curve as corresponding to an upper limit, *i.e.* when the regularization is switched off by $\Lambda \longrightarrow \infty$ in (13)). This leaves some space for improvements, *e.g.* by including effects discussed in [7]. Since the aim of the present paper is to highlight the importance of relativistic effects for the reaction under consideration, we insist to postpone a systematic evaluation of further details within the BS formalism to a separate investigation.

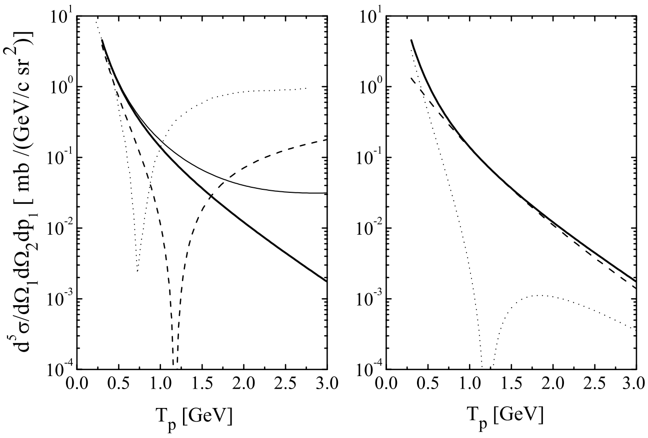

Fig. 4. Five-fold cross-section as a function of the kinetic energy T_p of the incident proton. Left panel: The dotted curve corresponds to a non-relativistic calculation, *i.e.*, to the case where only the "++" components in the $^1S_0$ state are taken into account and any Lorentz boost effect is ignored. The dashed curve depicts results of a calculation with all relativistic effects in "++" components. The solid thin curve is for the results of a complete calculation with taking into account all the relativistic effects including the contribution of P-waves in the wave function of the *pp* pair computed by (15) with $V_{31}(k,p,\mu_\pi^2)$ from (10), *i.e.*, without cut-off vertex form factors. The solid thick curve is the analog to the thin one but with taking into account the vertex form factor (13). The two protons are supposed to be detected in forward direction, *i.e.*, $\theta_1 = \theta_2 = 0°$. Right panel: The S-wave (dotted curve) and D-wave (dashed curve) contributions separately. Solid curve as in the left panel.

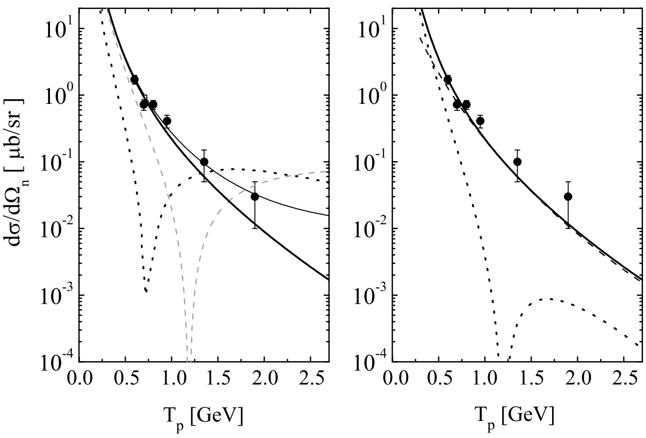

Fig. 5. Differential cross-section in the center of mass integrated over the excitation energy E_x as a function of the kinetic energy T_p of the incident proton. Notation is as in fig. 4. Experimental data are from [4].

The right panels in figs. 4 and 5 illustrate the contribution to the cross-sections of S and D components in the BS amplitude of the deuteron, *i.e.*, the contribution from the lower part of the diagram, fig. 1; all curves in the right panels have been obtained with taking into account the P-waves and form factors in the upper vertex of the diagram. It is clearly seen that in the whole range of the kinetic energy T_p the contribution of the D-waves in the deuteron dominates in the lower part of the diagram. This is an important circumstance which can generate ambiguities in non-relativistic calculations. So, since in the considered range of the intrinsic momenta the non-relativistic deuteron momentum distribution computed within different model potentials, such as Bonn or Paris group potentials, manifests a rather different behaviour, the final results become sensitive to the used potential (cf. results of [5] and [7]). In contrast, covariant relativistic calculations of the momentum distribution, obtained within different formalisms, *e.g.*, Bethe-Salpeter approach [11,16] or Gross equation [22] give basically identical results [18]. Note also that, to large extent, the non-relativistic Paris and RSC potentials provide the same momentum distributions as in relativistic approaches.

Finally, note that, as demonstrated in refs. [8,12] for reactions of pd and in near-threshold ed disintegration, the inclusion of P-waves exactly recovers the non-relativistic calculation with taking into account the $N\bar{N}$ pair production effects. Hence, in our case this is a hint that covariant calculations within the relativistic spectator mechanism contain already some contributions beyond the one-nucleon-exchange mechanism in its traditional non-relativistic meaning. Explicit calculations [5] of the meson-exchange corrections show that within the traditional effective meson-nucleon theory, with phenomenological parameters fitted from the NN scattering data, a satisfactorily description of data cannot be achieved.

5 Summary

In summary, with account to the recent data [4] of the reaction $pd \to (pp)n$ we present first results of a calculation within a covariant approach based on the Bethe-Salpeter formalism. Our approach relies on a straightforward application of the relativistic one-nucleon-exchange approximation. While effects beyond this approximation deserve further systematic investigations, we can emphasize that relativistic effects (Lorentz boost, negative-energy P components) in the description of the final pp pair are important and responsible for the smooth decline of the cross-section. We consider the process (1) as a unique example where the impact of the relativistic effects completely changes the non-relativistic picture, thus illustrating the importance of a consistent relativistic approach to the problem.

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