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Effects of the Tucson-Melbourne three-nucleon force in the proton-deuteron breakup process at $E_p = 65$ MeV

M. Allet[a], K. Bodek[a,1], J. Golak[c], W. Glöckle[b], W. Hajdas[a], D. Hüber[b], L. Jarczyk[c], H. Kamada[b], St. Kistryn[c], J. Lang[a], R. Müller[a], O. Naviliat-Cuncic[a], J. Smyrski[c], J. Sromicki[a], A. Strzałkowski[c], H. Witała[c], J. Zejma[a,1]

[a] *Institut für Teilchenphysik, Eidgenössische Technische Hochschule, Hönggerberg HPK, CH-8093 Zürich, Switzerland*
[b] *Institut für Theoretische Physik II, Ruhr Universität, Universitätstraße 150, D-44780 Bochum, Germany*
[c] *Institute of Physics, Jagellonian University, ul. Reymonta 4, PL-30059 Kraków, Poland*

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Abstract

We present the calculated cross sections and vector analyzing powers using the Bonn B nucleon-nucleon potential and the Tucson-Melbourne three-nucleon force (*3NF*) for six collinearity and quasi-free scattering breakup configurations. These calculations are compared to the results of the recent kinematically complete *pd* experiments at $E_p = 65$ MeV. The Tucson-Melbourne *3NF*, adjusted together with the Bonn B potential to reproduce the triton binding energy, leads to small effects both in cross sections and analyzing powers in all six studied configurations.

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1. Introduction

The three-nucleon (*3N*) system plays a special role in the study of the nucleon-nucleon (*NN*) interaction. It is the simplest few-nucleon system, in which it is possible to get an exact solutions for both bound and continuum states, and thus it is particularly suitable for testing the underlying nuclear dynamics. The presence of a third nucleon may introduce an additional term in the potential part of the nuclear Hamiltonian not present in the *2N* subsystems, the so-called three-nucleon interaction. An interesting question arises: is a simple picture of three nucleons interacting pairwise with a free *NN* potential sufficient or do we have to supplement it by a three-nucleon force (*3NF*) in order to understand *3N* systems?

In the past ^{3}H and ^{3}He nuclei, the two *3N* bound states existing in nature, were extensively studied using modern *NN* interactions as well as different *3NF* [1]. These studies show that all existing realistic *NN* potentials underbind ^{3}H by about 0.8 MeV. For local *NN* interactions this difference can be attributed to a *3N* force. For nonlocal *NN* forces, eg Bonn potentials [2,3], some part of this difference can be ascribed to nonlocality, leaving smaller gap between experimental and theoretical binding energy. From different models of a three-nucleon interaction the most extensively used was a 2π-exchange model of the *3NF* proposed

[1] On leave from Institute of Physics, Jagellonian University, Cracow, Poland.

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by the Tucson-Melbourne Collaboration (*TM 3NF*) [4]. Such a force has the largest range due to the small mass of exchanged π-mesons.

The *3N* continua, the nucleon-deuteron elastic scattering and deuteron breakup processes, offer a much broader opportunity for testing the underlying nuclear dynamics than the *3N* bound state. The deuteron breakup process is of special interest due to the possibility of choosing different geometries of the outgoing nucleons making it more selective with respect to the interaction. The theoretical formalism together with the corresponding numerical algorithms has been developed which allows to solve the *3N* Faddeev equations in continuum using any type of realistic *2N* forces [5] with the same rigorousness and precision as in case of *3N* bound state. The same applies for the inclusion of *3NF*'s [6], though present day computer resources still pose some limitations.

From the bulk of *3N* data analyzed by us up to now we have found that a simple Hamiltonian composed of realistic 2-body *NN* forces only describes quite well the elastic *Nd* scattering and the breakup process [7]. Some possible important exceptions are pointed out in Ref. [7]. This description is quite stable with respect to replacing one *NN* force by another, as long as they describe the *2N* data equally well. Thus the present *NN* forces leave only a little space for *3N* force effects. This conclusion seems to be supported by recent theoretical studies based on an effective chiral Lagrangian approach [8].

In this work we study the effects of the $\pi - \pi$ exchange *TM 3NF* in specific, kinematically complete configurations of the deuteron breakup measured recently at PSI using a proton beam with an energy E_p = 65 MeV [9,10]. These configurations include the so-called quasi-free scattering (QFS) and collinearity geometries, where the not-detected nucleon (neutron) is at rest in the laboratory and c.m. system, respectively.

2. Theory

The inclusion of a *3NF*, V_4, into the *3N* scattering formalism amounts to solving the set of coupled equations for two operators T and T_4 of the form

$$T = tP + tG_0T_4 + tPG_0T, \tag{1}$$

$$T_4 = (1+P)t_4 + (1+P)t_4G_0T. \tag{2}$$

Here t is the 2-body t-operator driven by the *2N* interaction, G_0 is the free *3N* propagator, P is a sum of cyclic and anticyclic permutations of three nucleons and t_4 is generated by V_4 through a Lippmann-Schwinger type equation:

$$t_4 = V_4 + V_4G_0t_4. \tag{3}$$

The operators T and T_4 determine the transition operator U_0 for the breakup process

$$U_0 = (1+P)T + T_4. \tag{4}$$

Both operators T and T_4 act on the incoming channel state composed of the deuteron wave function and a momentum eigenstate of the relative nucleon-deuteron motion. The breakup amplitude is then given by $\langle\phi_0|U_0|\phi\rangle$ with the state ϕ_0 describing the free motion of three outgoing nucleons.

Iterating the set of equations (1), (2) reveals the underlying physics of multiple scattering in terms of corresponding pure *2N* and genuine *3N* transitions. The set (1), (2) is solved in a perturbation approach in powers of V_4. The various orders in V_4 are summed up by the Padé method. For general background, details of the formalism and the numerical performance we refer to Refs. [5,6,11,12].

We solved the set (1), (2) using the meson-exchange Bonn B potential [2] as the *NN* interaction. The *3NF* was chosen to be the 2π-exchange three-nucleon interaction in the form proposed by the Tucson-Melbourne collaboration [4]. Its effect depends on the value of the cut-off parameter Λ_π in the strong π-*NN* formfactor. We performed calculations taking the "standard" value [6] $\Lambda_\pi = 5.8\mu$ (μ = 139.6 MeV) and also with $\Lambda_\pi = 4.55\mu$. The first one leads together with the Bonn B potential to overbinding the triton by about 2 MeV. The *TM 3NF* using the second value of Λ_π together with the Bonn B potential reproduces the experimental triton binding energy. In our calculations both the *2N* and the *3N* forces were allowed to act in all partial wave states with total two-body subsystem angular momenta $j \leq 2$. Such a restriction does not lead to a completely convergent results at the energy of the present study. We know that $j = 3$ *NN*-force components influence noticeably some observables at this

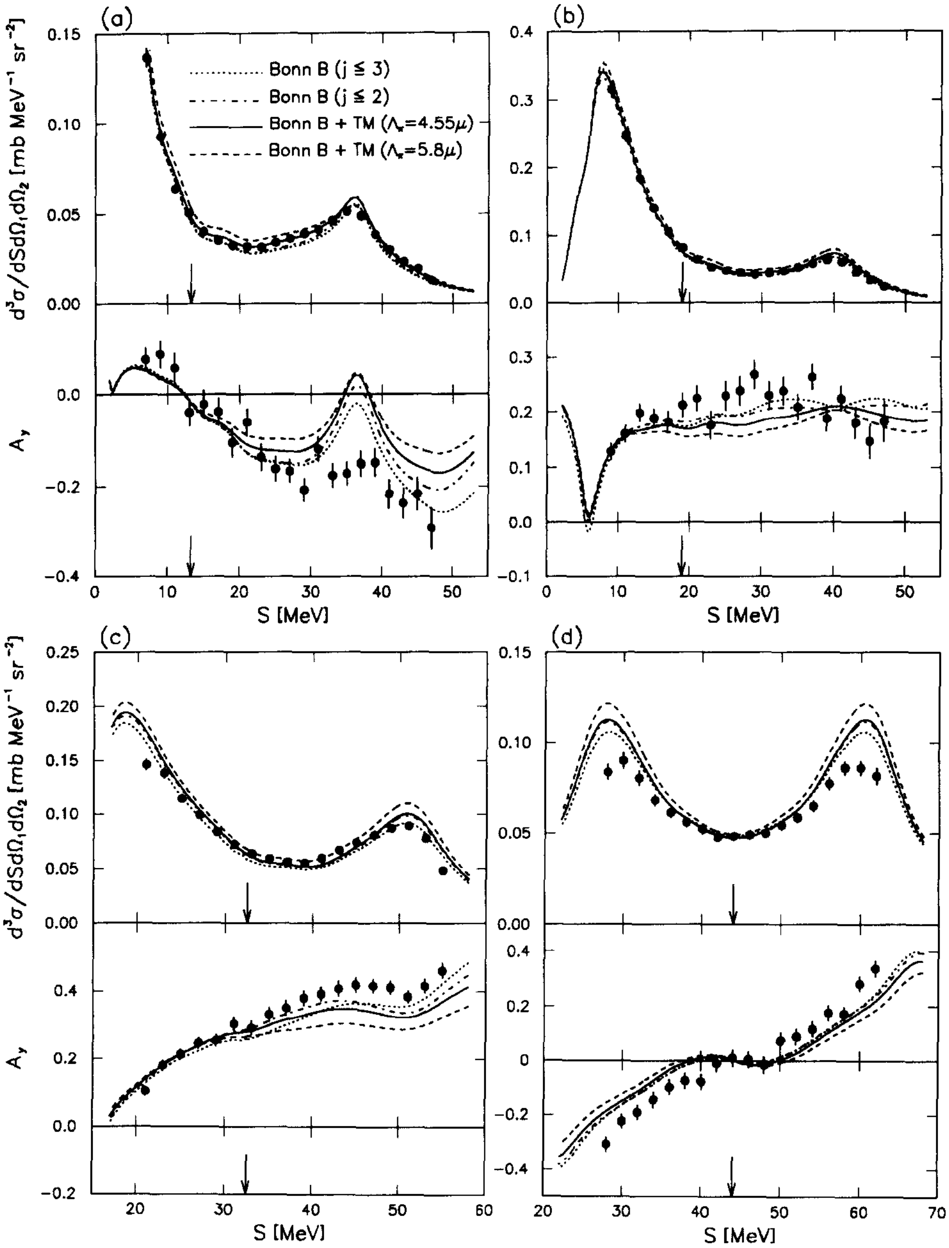

Fig. 1. Cross section and analyzing power A_y for the collinearity configurations at E_p^{lab} = 65 MeV, (a) (ϑ_1 = 20.0°, ϑ_2 = 116.2°, φ_{12} = 180.0°), (b) (30.0°, 98.0°, 180.0°), (c) (45.0°, 75.6°, 180.0°) and (d) (59.5°, 59.5°, 180.0°) as a function of the arc-length S along the kinematical curve. The full dots show our experimental data [9,10]. The dotted and dash-dotted curves are the theoretical predictions obtained using the Bonn B potential with $2N$-angular momentum space limited to $j \leq 3$ and $j \leq 2$, respectively. The dashed and solid curves result when in addition to the Bonn B potential ($j \leq 2$) the *TM 3NF* is included with the cut-off parameter $\Lambda_\pi = 5.8\mu$ and $\Lambda_\pi = 4.55\mu$, respectively. The arrows show the exact position where the collinearity condition is fulfilled.

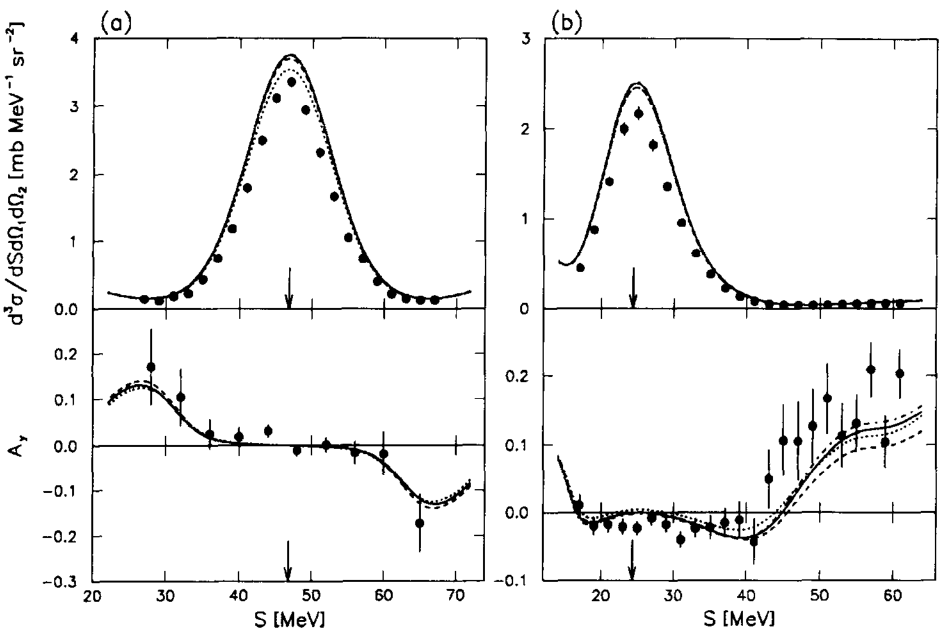

Fig. 2. The same as Fig. 1 but for the *pp*-QFS configuration at (a) (44.0°, 44.0°, 180.0°) and (b) (30.0°, 59.5°, 180.0°). The arrows show the exact position where the QFS condition is fulfilled.

energy. However, it is sufficient to get a first insight into the magnitudes of possible *3NF* effects. In order to see the magnitude of $j = 3$ contributions we performed also calculations with the Bonn B potential only taking into account all $j \leq 3$ partial waves.

3. Comparison with experiment and conclusions

The fully converged theory obtained with different *NN* interactions only have been presented in our previous papers [9,10]. Results obtained with the Bonn B potential are showed in this study in figures by the dotted lines. All measured cross sections and analyzing powers are compared to the theoretical predictions evaluated in a "point-like" geometry. This makes sense since for the chosen configurations the finite geometry and resolution effects of the experimental setup are negligible. For a more detailed discussion we refer to [9,10].

Comparison of the predictions obtained without and with the *TM 3NF* using $\Lambda_\pi = 5.8\mu$ shows that the *3NF* effects depend significantly on the configuration and the region along the kinematical curve. The large effects (up to about 25%) are seen in the region of collinearity (Fig. 1). The significantly smaller effects (about 2%) appear in case of the QFS configurations – Fig. 2. Practically everywhere the inclusion of the *TM 3NF* increases the cross section for the collinearity configurations – the new theoretical values overestimate the measured ones. For the QFS case the cross section is decreased slightly around the maximum – but still staying above the data.

Taking the value $\Lambda_\pi = 4.55\mu$ for the *TM 3NF*, which together with the Bonn B potential reproduces the triton binding energy, reduces the *3NF* effects and makes them nearly negligible, especially in case of the QFS configurations.

The vector analyzing powers in all six studied configurations are more influenced by the *TM 3NF* than the corresponding cross sections. The effects are also cut-off dependent and even in case of $\Lambda_\pi = 4.55\mu$ they can be seen. However, in nearly all cases the inclusion of the *TM 3NF* increases disagreement between the theory and the experimental data.

Summarizing, we have found that the size of the *TM 3NF* effects in the *pd* breakup at the energy of $E_p = 65$ MeV are strongly cut-off dependent. For the value of the cut-off parameter $\Lambda_\pi = 4.55\mu$, which reproduces the experimental triton binding energy, these effects are negligible for both cross sections and analyzing powers for QFS configurations, and are very small for collinearity configurations. In nearly all cases inclusion of the *TM 3NF* brings theory away from the measured values – some improvement can be seen only in the cross section of the collinearity configuration (20°, 116°, 180°).

It should be, however, pointed out that the *TM 3NF* was not derived in the same theoretical framework as the Bonn B potential. It would be interesting to find out how far this incompatibility is important by performing calculations with both *NN* and *3NF* forces derived consistently in the same theoretical framework as e.g. in [13]. Such a work is under way.

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