# Evidence for large discrepancies between data and calculations for the kinematically incomplete neutron-deuteron breakup reaction

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A review of kinematically incomplete $n$-$d$ breakup data and their comparison to rigorous 3$N$ calculations using realistic nucleon-nucleon interactions revealed unexplained differences of more than 25% in regions where a large number of different three-nucleon configurations contribute to the cross section. [S0556-2813(96)02507-1]

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## I. INTRODUCTION

In Ref. [1] the results of rigorous three-nucleon (3$N$) Faddeev calculations performed for the kinematically incomplete neutron-deuteron ($n$-$d$) breakup reaction were compared to experimental proton energy spectra obtained at a nominal laboratory proton emission angle of $\theta_p = 0°$. At $E_n = 14$ MeV it turned out to be necessary to normalize the data of Shirato *et al.* [2] and Haight *et al.* [3] by about 20% in order to achieve agreement between data and calculations in the proton energy range below about 9 MeV. Figures 1(a) and 1(b) show the unnormalized data of Shirato *et al.* at $E_n = 14.1$ MeV, $\theta_p = 4.0°$ and Haight *et al.* at $E_n = 13.98$ MeV, $\theta_p = 1.6°$ in comparison to rigorous 3$N$ Faddeev calculations where the finite geometry of the experimental setup was taken into account using Monte Carlo techniques. Here, $\theta_p$ refers to the mean proton emission angle. The calculations shown employed the Bonn $B$ [4] nucleon-nucleon ($NN$) potential in a charge-dependent version [1]. The normalized experimental proton energy spectra are presented in Figs. 1(c) and 1(d) in comparison with the calculations referred to above. Here, the data of Shirato *et al.* and Haight *et al.* were normalized by 0.83 and 0.80, respectively. It was shown in Ref. [1] that the cross section $d^2\sigma/(d\Omega dE_p)$ in the energy region below 9 MeV is insensitive to the value of the ($n$-$n$) scattering length $a_{nn}$ used in the calculation, in contrast to the $n$-$n$ final-state-interaction (FSI) peak around $E_p = 11.8$ MeV. Furthermore, as can be seen from Fig. 2, the normalization factors are nearly independent of the $NN$ potential used in the 3$N$ calculations. In Fig. 2 proton energy spectra are given which were calculated with the $NN$ potentials Bonn $B$, Paris [5] and Nijmegen [6] at $E_n = 14$ MeV, $\theta_p = 4°$. Another important feature is the fact that in the energy range below about 9 MeV the theoretical, point-geometry calculations can be compared directly with the experimental data without any averaging over the experimental angular and energy spread. In order to support this statement, the solid curve in Fig. 3 presents a point-geometry calculation (Bonn $B$) based on $E_n = 14$ MeV, $\theta_p = 4°$. The dashed curve shows the associated finite-geometry calculation obtained by averaging point-geometry calculations over the angular and energy acceptance as well as over the energy spread and energy resolution of the experimental arrangement of Shirato *et al.* In contrast to the $n$-$n$ FSI region, both curves are in close agreement in the energy range below 9 MeV.

It should be noted that large normalization factors were found already in the original work [2,3]. There, in contrast to Ref. [1], the calculations based on simple potentials were normalized by 1.30 and 1.26, respectively, in order to describe the experimental data below the $n$-$n$ FSI enhancement. The data normalization factors found in Ref. [1] are of special concern since these two data sets were considered to be the most accurate data of its kind in the $n$-$n$ FSI region. If confirmed, this finding will have far reaching consequences with respect to our understanding of the low-energy $NN$ interaction and/or the importance of three-nucleon forces in the 3$N$ system. At 14 MeV only the $^1S_0$ and $^3S_1-{}^3D_1$ $NN$ force components contribute to the calculated proton energy spectrum. Therefore, the observed discrepancy is even more astonishing. On the other hand, very recently, the previously observed large difference between the measured and calculated $n$-$d$ breakup cross section for the space-star configuration at $E_n = 13$ MeV [7] has been confirmed [8]. There, the experimental cross section was found to be about 20% larger than the calculated cross section. In addition, this observable is also governed by the $^3S_1-{}^3D_1$ and $^1S_0$ $NN$ interactions and the calculated result is independent of the choice of the $NN$ interaction used in the 3$N$ calculation, as well.

In view of the observed discrepancy it is important to

 

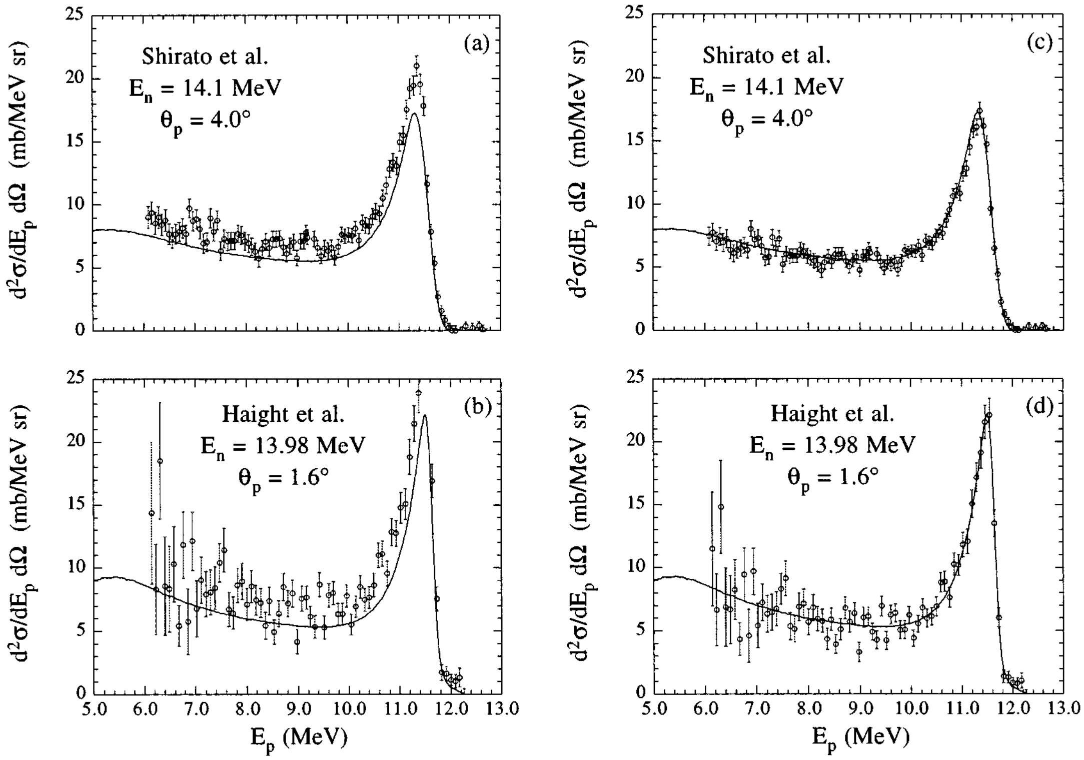


FIG. 1. Experimental proton energy spectra (dots with error bars) for the $^2$H$(n,p)nn$ reaction at incident neutron energy $E_n$ and mean proton emission angle $\theta_p$ in comparison to Monte Carlo simulations of the associated experimental setups using rigorous 3$N$ calculations employing the Bonn $B$ $NN$ potential. (a) $E_n$=14.1 MeV, $\theta_p$=4.0°, experimental data taken from Ref. [2], (b) $E_n$=13.98 MeV, $\theta_p$=1.6°, experimental data taken from Ref. [3]. (c) same as in (a), but data were normalized by a factor of 0.83, (d) same as in (b), but data were normalized by a factor of 0.80.

carefully scrutinize the available experimental information not only around $\theta_p$=0°, as was done in Ref. [1], but also at larger proton emission angles where the $n$-$n$ FSI is not the dominant feature in the observed proton energy spectrum. As stated earlier, this will allow us to directly compare point-geometry calculations with finite-geometry data. This procedure is not adequate in the $n$-$n$ FSI region where extensive Monte Carlo simulations are required [1]. Their accuracy is limited by the lack of accurate information about the angular and energy acceptance and energy resolution of the detectors employed for detecting the breakup protons in some of the experiments of interest.

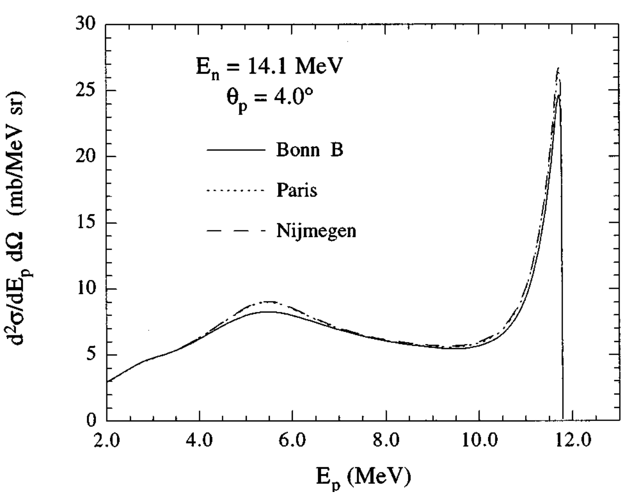


FIG. 2. Calculated proton energy spectra for the $^2$H$(n,p)nn$ reaction at $E_n$=14.1 MeV and $\theta_p$=4.0° using different realistic $NN$ potential models. Solid curve, Bonn $B$; dotted curve, Paris; dashed curve, Nijmegen potential.

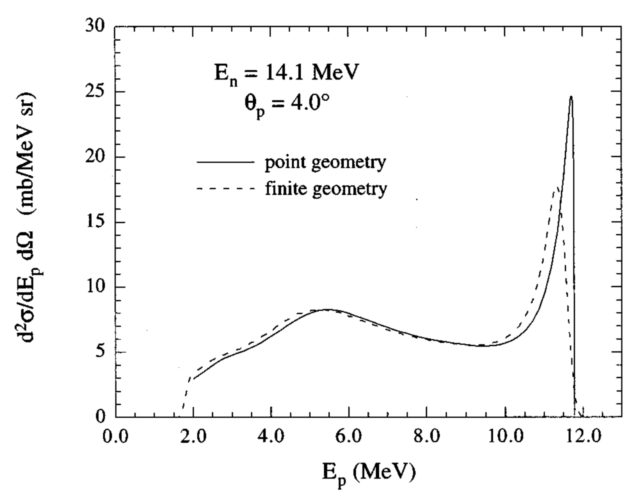


FIG. 3. Calculated point-geometry (solid curve) and finite geometry (dashed curve) proton energy spectrum for the $^2$H$(n,p)nn$ reaction using the experimental arrangement of Shirato *et al.*, Ref. [2], at $E_n$=14.1 MeV and $\theta_p$=4.0°. Below 9 MeV, the point-geometry and finite-geometry calculations agree rather well.

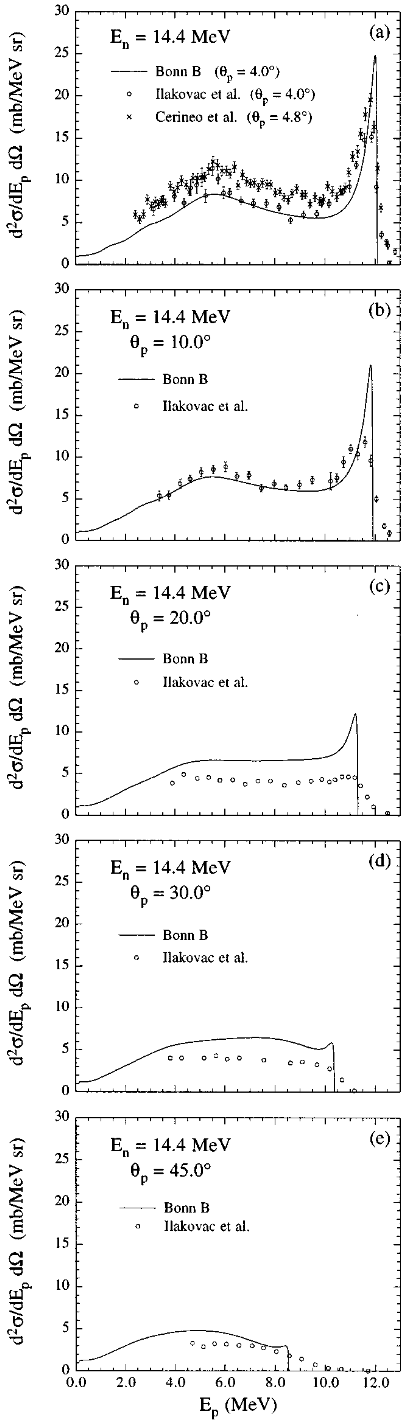


FIG. 4. Experimental proton energy spectra for the reaction $^2$H$(n,p)nn$ in comparison to rigorous point-geometry 3*N* calculations (solid curve) using the Bonn *B NN* potential. (a) Open dots, data of Ilakovac *et al.*, Ref. [9] at $E_n = 14.4$ MeV and $\theta_p = 4.0°$; crosses, data of Cerineo *et al.*, Ref. [12] at $E_n = 14.4$ MeV and $\theta_p = 4.8°$. (b) Data of Ilakovac *et al.*, Ref. [9] at $E_n = 14.4$ MeV and $\theta_p = 10.0°$. (c)–(e) Data of Ilakovac *et al.*, Ref. [11] at $E_n = 14.4$ MeV and $\theta_p = 20°$, 30°, and 45°.

## II. COMPARISON OF DATA AND RIGOROUS CALCULATIONS

According to our knowledge, the first accurate proton energy spectra obtained from the kinematically incomplete *n*-*d* breakup reactions were reported in 1961 by Ilakovac *et al.* (Zagreb group) [9] using 14.4 MeV neutrons and mean proton emission angles $\theta_p$ of 4° and 10°. These data are shown in Figs. 4(a) and 4(b) (open dots) in comparison with our rigorous 3*N* calculations. These and all the following calculations are point-geometry calculations and employ the Bonn *B NN* potential with charge dependence included in the $^1S_0$ state, unless stated otherwise. For details concerning the 3*N* calculations we refer to Ref. [10]. As can be seen, the data are in good agreement with the calculations in the region below the *n*-*n* FSI peak. In a subsequent publication [11] the same group reported data at $E_n = 14.4$ MeV for $\theta_p = 20°$, 30°, and 45°. These data [see Figs. 4(c)–4(e) (open dots)] are in considerable disagreement with the present 3*N* calculations. Shortly afterwards, the Zagreb group (Cerineo *et al.*) published a very detailed proton spectrum which was obtained with 14.4 MeV neutrons at $\theta_p = 4.8°$ [12]. This spectrum is shown in Fig. 4(a) (crosses). The cross-section data are about 25% larger than the previous data of the Zagreb group (Ilakovac *et al.*) reported at $\theta_p = 4.0°$, and consequently, are in serious disagreement with the 3*N* calculations. The systematic uncertainties involved in extracting absolute cross sections from the measured proton energy distribution are not included in the error bars shown in Fig. 4. The overall uncertainty of the absolute cross section quoted by Ilakovac *et al.* is ±8%. The data of Cerineo *et al.* have an overall absolute cross-section uncertainty of ±12%. In both cases the data were normalized to the neutron-proton (*n*-*p*) cross section by replacing the deuterated polyethylene foil $(C^2H_2)_n$ by a regular polyethylene foil $(C^1H_2)_n$. In addition, the normalization of the data of Cerineo *et al.* was checked by normalizing to *n*-*d* elastic scattering. Both normalization procedures agreed within 2.5%. Taking into account the absolute normalization uncertainties, the apparent disagreement between the two data sets of Ilakovac *et al.* and Cerineo *et al.* may not be as serious as Fig. 4 indicates. In other words, the close agreement between the data of Ilakovac *et al.* and the 3*N* calculations at $\theta_p = 4°$ and $\theta_p = 10°$ may be fortuitous.

In 1965 Voitovetskii *et al.* (Kurchatov group) [13] reported a proton spectrum obtained with $E_n = 13.9$ MeV neutrons at $\theta_p = 4.5°$. This spectrum is shown in Fig. 5(a) along with our 3*N* calculations. Although this spectrum does not extend to low energies, it agrees very well with the calculations in the energy range of interest, i.e., below 9 MeV. Voitovetskii *et al.* normalized their data to *n*-*d* elastic scattering. The quoted absolute accuracy of the differential cross-section data is ±4%. The Kurchatov group [14] also measured proton energy distributions at $\theta_p = 10°, 15°$, and 20°. Rather than representing the actual data, the Kurchatov group published the dashed curves shown in Figs. 5(b)–5(d). Information about the statistical uncertainty of the data is not given in Ref. [14]. Unfortunately the energy range of interest for our studies is even smaller than the one shown in Fig. 5(a). Nevertheless, the agreement between the ''data'' and our 3*N* calculations is very good.

In 1965 Debertin *et al.* [15] reported *n*-*d* breakup proton energy spectra at $E_n = 14.1$ MeV for $\theta_p = 7.5°, 15°, 30°, 45°$, and 55°. Except for $\theta_p = 7.5°$ and 55°, the data below 9 MeV are in good agreement with our 3*N* calculations (see Fig. 6). At $\theta_p = 7.5°$ the data are somewhat higher

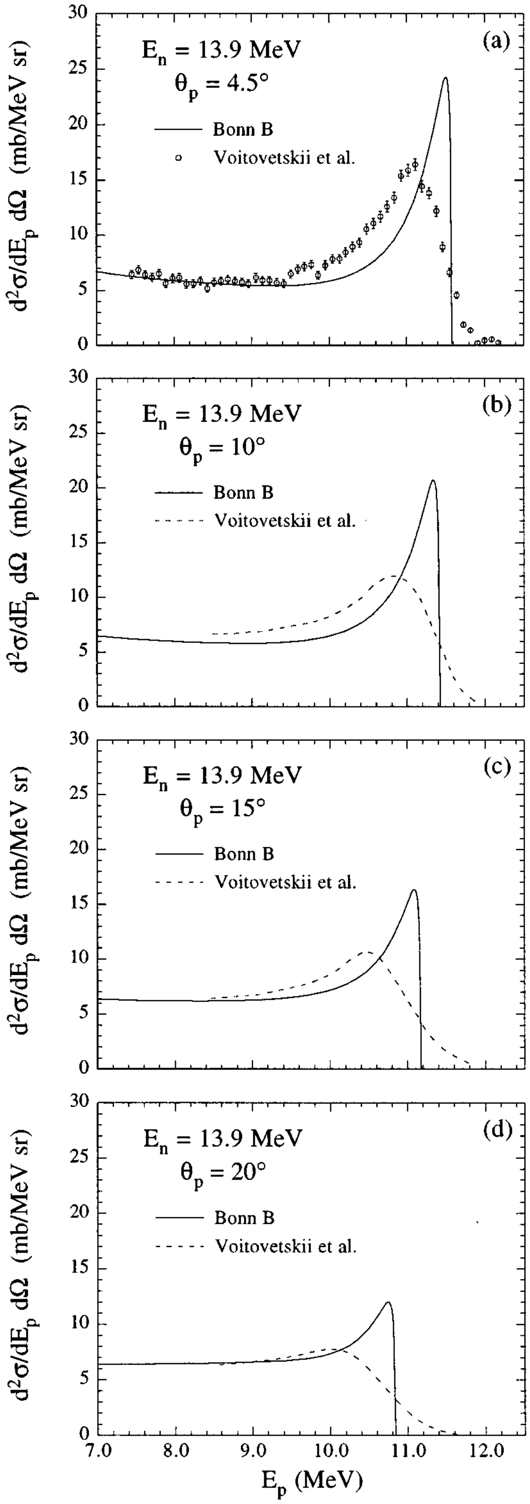


FIG. 5. Experimental proton energy spectra of Voitovetskii *et al.*, Refs. [13,14] for the reaction ${}^{2}\mathrm{H}(n,p)nn$ at $E_n = 13.9$ MeV in comparison to rigorous point-geometry $3N$ calculations using the Bonn $B$ $NN$ potential at $\theta_p = 4.5°, 10°, 15°$, and $20°$.

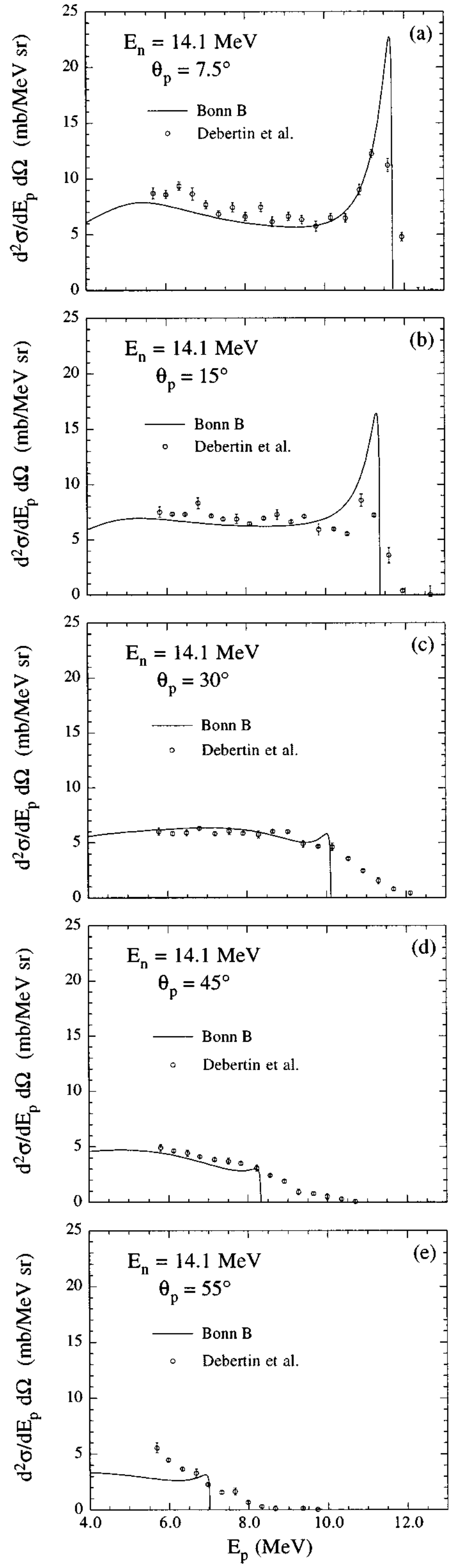


FIG. 6. Same as Fig. 5. The neutron energy is $E_n = 14.1$ MeV and the experimental data at $\theta_p = 7.5°, 15°, 30°, 45°$, and $55°$ are from Debertin *et al.*, Ref. [15].

than the $3N$ predictions. The absolute scale uncertainty of the cross section data is $\pm 10\%$.

The data of Bond [16] at $E_n = 14$ MeV are limited to the $n$-$n$ FSI peak and therefore are not helpful for our purpose. Similarly, the data of Shirato and Koori [17] at $E_n = 14.1$ MeV, $\theta_p = 3.9°$ do not extend below 9 MeV.

The most complete investigation of $n$-$d$ breakup proton spectra was performed by Koori [18], ten years after the pioneering work of the Zagreb group. Proton spectra were obtained between $\theta_p = 4.0°$ and $59.7°$ using 14.1 MeV incident neutrons. The data are shown in Fig. 7 in comparison to

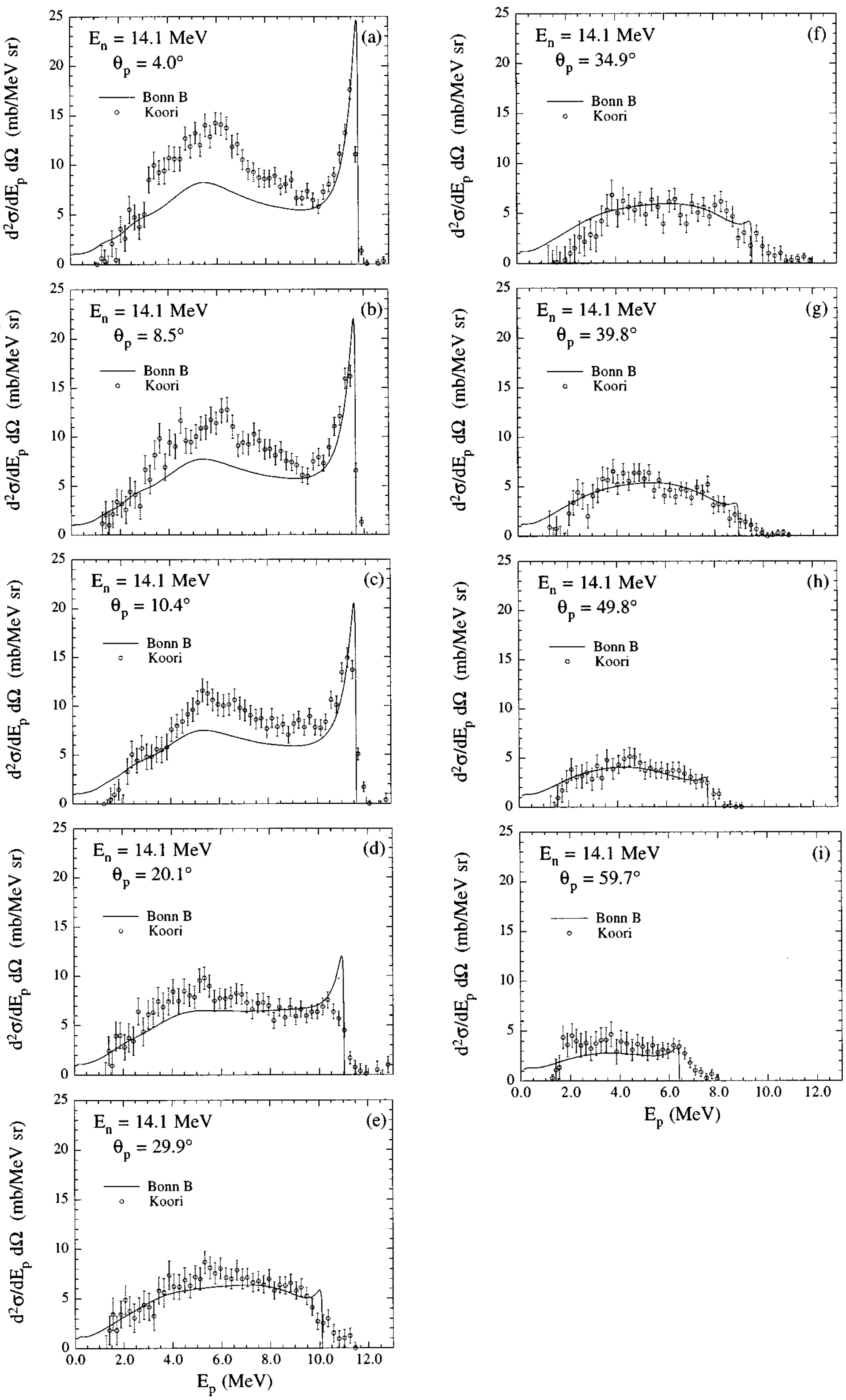


FIG. 7. Same as Fig. 5. The neutron energy is $E_n = 14.1$ MeV and the experimental data are from Koori, Ref. [18] at $\theta_p = 4.0°$, 8.5°, 10.4°, 20.1°, 29.9°, 34.9°, 39.8°, 49.8°, and 59.7°.

our 3*N* calculations. Clearly, data and calculations disagree at $\theta_p = 4.0°$, 8.5°, and 10.4°. However, already at 20.1° the agreement is satisfactory and becomes quite good beyond this angle. The overall absolute normalization uncertainty of the data of Koori is only $\pm 3.3\%$. This relatively small uncertainty is supported by the fact that the *n-p* differential cross section, measured previously with the same apparatus by Tanaka *et al.* [19] at the same incident neutron energy is in reasonable agreement with phase-shift predictions and previous experimental data. Therefore, we trust the quoted accuracy of the data of Koori.

## III. DISCUSSION

We will begin our discussion by concentrating on the data and calculations at small proton emission angles [Figs. 4(a)–

TABLE I. Difference between 3*N* calculations and data at $E_p = 6$ MeV for different proton emission angles $\theta_p$. In the case of Voitoveskii *et al.*, $E_p = 8.5$ MeV was used and the first and second value given in columns 3 and 4 refer to the original normalization and our renormalization, respectively. In the case of Debertin *et al.*, we used $\theta_p = 7.5°$ instead of $\theta_p = 4°$. The plus (or minus) sign in columns 3–5 means that the calculated cross section is larger (or smaller) than the experimental data.

| Reference | Normalization Uncertainty (in %) | Difference between calculation and data (in %) $\theta_p \approx 4°$ | $\theta_p \approx 15°$ | $\theta_p \approx 40°$ |
|---|---|---|---|---|
| Ilakovac *et al.* | ±8 | 0 | +10 | +25 |
| Cerineo *et al.* | ±12 | −40 | | |
| Voitoveskii *et al.* | ±4.4 | 0, 0 | 0, +20 | |
| Debertin *et al.* | ±10 | −15 | −10 | ≈0 |
| Koori | ±3.3 | −70 | −25 | ≈0 |
| Shirato *et al.* | ±3.3 | −20 | | |
| Haight *et al.* | ±8 | −25 | | |

7(a)], since they are most relevant to the normalization issue displayed in Fig. 1. Our present investigations provide additional support for the stunning observation referred to in the Introduction that proton energy distributions obtained from the kinematically incomplete *n*-*d* breakup reaction at forward angles are in clear disagreement with the results of rigorous 3*N* calculations that employ realistic *NN* interactions. The cross section of the three most recent data sets (Koori [18] 1972, Shirato *et al.* [2] 1973, and Haight *et al.* [3] (1977) is considerably larger than the one obtained from 3*N* calculations. In addition, the data of Cerineo *et al.* [12] [1964, see Fig. 4(a)] support this observation. Furthermore, as stated in Ref. [18], the spectrum of Koori at $\theta_p = 4.0°$ agrees with the one of Ref. [2], considering the statistical and absolute normalization uncertainties. The cross section measured by Debertin *et al*. at $\theta_p = 7.5°$ [see Fig. 6(a)] is also slightly larger than the 3*N* calculations in the region of interest. This fact may also be used to support our findings at $\theta_p = 4°$ and 4.8°. Table I summarizes the situation. Here column 2 represents the absolute normalization uncertainty of the data. Columns 3–5 give the difference (in %) between calculations and data at $\theta_p \approx 4°$, 15°, and 40°. In the few cases where data were not available at the quoted angles, we interpreted between adjacent data sets. Clearly, in five out of seven data sets, the 3*N* calculations predict cross sections that are between 15% and 70% smaller than the experimental data at $\theta_p \approx 4°$ (see column 3). Only the data of Ilakovac *et al.* and Voitovetskii *et al.* are in agreement with the 3*N* calculations at these forward angles.

Considering now the proton spectra obtained for $\theta_p \geqslant 10°$ we notice that the most detailed and accurate investigations were performed by Koori [18] [see Figs. 7(b)–7(i)]. With increasing proton emission angle the discrepancy between data and 3*N* calculations becomes less noticeable and seems to disappear almost completely for $\theta_p \geqslant 30°$. Clearly, this tendency is also present in the data of Debertin *et al.* [15] between $\theta_p = 7.5°$ and 45° (see Fig. 6). More quantitative information is given in columns 4 and 5 of Table I. The data of Ilakovac *et al.* [9,11] exhibit exactly the opposite tendency [see Figs. 4(c)–4(e)]. Here the agreement between data and 3*N* calculations decreases with increasing $\theta_p$. Finally, the data of Voitovetskii *et al.* [14] at $\theta_p = 10°, 15°$, and 20° appear to be in excellent agreement with the 3*N* calculations [see Figs. 5(b)–5(d)], although the available energy range for our comparison is even more limited than at $\theta_p = 4.5°$. Information concerning the absolute normalization is not given in Ref. [14]. Suppose the data were also normalized to the *n*-*d* elastic data of Seagrave [20], as was done at $\theta_p = 4.5°$ by the same group [13]. At $\theta_d = 3.5°$ and $\theta_d = 5.5°$, the data of Seagrave are in good agreement with rigorous 3*N* calculations [21]. Since at $\theta_d = 10°$ the data of Seagrave are 17% larger than the results of 3*N* calculations [21] suggest, the accordingly renormalized data of Voitovetskii *et al.* would be in even better agreement with the 3*N* calculations. However, with increasing $\theta_d$, the data of Seagrave deviate considerably from 3*N* calculations. At $\theta_d = 20°$ the data of Seagrave are about 50% larger than the results of 3*N* calculations, which agree well with recent experimental data [21]. Therefore, the renormalized data of Voitovetskii *et al.* at $\theta_p = 15°$ and 20° are well below the 3*N* calculations and, in fact, the data at $\theta_p = 20°$ are in fair agreement with the data of Ilakovac *et al*. at the same angle. In Table I, the second value listed for Voitovetskii *et al.* refers to the renormalized data.

## IV. SUMMARY AND CONCLUSION

In summary, we conclude that for the majority of the available experimental *n*-*d* breakup cross sections the data at small proton emission angles $\theta_p$ are considerably larger than predictions of rigorous 3*N* calculations based on realistic *NN* interactions. The two data sets (Ilakovac *et al.* and Voitoveskii *et al.*) that are found to be in good agreement with the calculations at $\theta_p \approx 4°$, are in serious disagreement with 3*N* calculations at larger proton emission angles. Here, the measured cross section is lower than the theoretical predictions. Ironically, exactly the opposite tendency is observed for the other two data sets (Koori and Debertin *et al.*) that extend to larger $\theta_p$. Although their data disagree at small $\theta_p$ with the 3*N* calculations, the agreement improves with increasing $\theta_p$. In fact, good agreement is found for $\theta_p \geqslant 30°$. This observation implies that renormalization factors would bring the data of Ilakovac *et al.* and the renormalized data of Voitoveskii *et al.* in reasonable agreement with all the other data discussed in the present work. Of course, the latter data could be renormalized as well to establish close agreement with the data of Ilakovac *et al.* and the renormalized data of Voitoveskii *et al.* Either way, the large

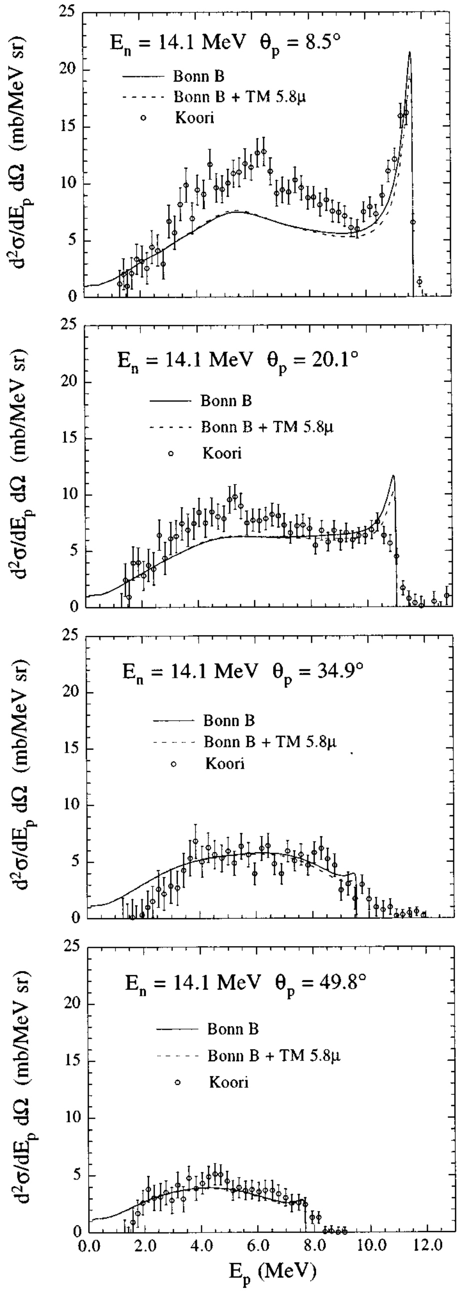


FIG. 8. Same as Figs. 7(b), 7(d), 7(f), and 7(g) (top to bottom), but the rigorous 3*N* calculations include the Tucson-Melbourne three-nucleon force (dashed curves).

discrepancy between experimental data and rigorous 3*N* calculations will persist, i.e., either at small or large proton emission angles.

Except for the *n*-*n* FSI region around $E_p = 11.8$ MeV, the spectrum shown in Fig. 4(a) is the result of an averaging process over a large number of possible 3*N* configurations in which the proton moves forward (i.e., in the direction of the incident neutron momentum) in the laboratory frame. The strong enhancement noticed at $E_p = 5.6$ MeV is expected to be caused by the *n*-*p* FSI [9]. However, in general, due to the averaging process, it is not possible to single out any specific 3*N* configuration that can be made responsible for the observed discrepancy.

Since the calculated cross section is predominantly determined at 14 MeV by the $^1S_0$ and $^3S_1-^3D_1$ *NN* interactions, it appears unreasonable to blame deficiencies in these *NN* force components for the observed discrepancy. Although we realize that the *n*-*p* $^1S_0$ and $^3S_1-^3D_1$ and the *n*-*n* $^1S_0$ phase shifts have not yet been determined in a model-independent way from experimental data, on-shell shortcomings of these phase shifts are most likely not the source of the problem. Otherwise, irregularities and deviations must have been noticed in the past in other observables as well.

Of course, the question of the influence of three-nucleon (3*N*) force effects on the *n*-*d* breakup cross section remains to be investigated. Rigorous 3*N* calculations that include the Tucson-Melbourne (TM) [22] 3*N* force were presented in Ref. [23]. These calculations were restricted to small $\theta_p$. At $E_n = 14.1$ MeV, $\theta_p = 4°$ very good agreement was obtained below $E_p = 9$ MeV with 3*N* calculations based on realistic *NN* interactions only. In Fig. 8 we present 3*N* calculations at $E_n = 14.1$ MeV which include the TM 3*N* force also at large $\theta_p$. As can be seen, the TM 3*N* force has practically no effect on the cross section below $E_p = 9$ MeV. Therefore, the discrepancy between data and calculations revealed in the present work remains unexplained.

We conclude that it is important to remeasure the cross section for the kinematically incomplete *n*-*d* breakup reaction at $E_n = 14$ MeV for proton emission angles $\theta_p < 60°$ using nowadays experimental techniques. Only with new and accurate data can the present observation of large discrepancies between data and rigorous 3*N* calculations be explored in a constructive way.

## ACKNOWLEDGMENTS

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