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Neutron-neutron final-state interaction in the ^{2}H(n, p)2n reaction at $E_n = 17.4$ MeV

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The neutron-neutron (nn) final-state interaction has been investigated in the $n+d \rightarrow p+2n$ reaction in kinematically incomplete geometry at $E_n = 17.4$ MeV, detecting the protons emitted around zero degrees. Absolute cross-section data for the neutron-deuteron breakup reaction were obtained via (n, d) elastic scattering, which was measured simultaneously. The data were analyzed by means of detailed Monte Carlo simulations based on rigorous three-body calculations using CD-Bonn and two other high-quality potentials for the nucleon-nucleon interaction. The breakup spectrum is described very well on an absolute scale over the entire energy range investigated. The value of the nn scattering length deduced from the cross section in the FSI peak is $a_{nn} = -16.5 \pm 0.9$ fm, where the error indicates the combined statistical and systematic uncertainty.

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I. INTRODUCTION

Since the mid-1990s, great progress has been made in the theoretical description of the three nucleon (3N) system. In particular, the $n+d$ reaction, where no Coulomb forces are involved, is generally described very well by present-day, dynamically exact Faddeev-type calculations with realistic nucleon-nucleon (NN) forces, both in the elastic and in the breakup channel. However, there are a few striking exceptions. For instance, the theory cannot reproduce the measured nucleon and deuteron vector-analyzing powers at low energies, $A_y(\theta)$ and $iT_{11}(\theta)$, respectively; this is the well-known analyzing power puzzle [1]. A second example is the so-called space-star anomaly: the breakup cross section is not described correctly if the three nucleons fly apart in a symmetric star oriented perpendicular to the beam direction [2]. Finally, whereas neutron-proton (np) quasifree scattering (QFS) in the $n+d$ reaction is reproduced perfectly by the theory [3,4], the measured cross section for neutron-neutron (nn) QFS is 15–20% larger than predicted [4,5].

In addition, a long-standing problem exists with kinematically *incomplete* experiments when used for the determination of the nn scattering length a_{nn} [6]. At forward angles in the $n+d \rightarrow p+2n$ reaction, the nn final-state interaction (FSI) produces a prominent peak at the high-energy end of the proton spectrum where the cross section is sensitive to a_{nn}. However, attempts to determine a_{nn} in this way have failed to produce consistent results. In particular, two similar experiments at 14 MeV, performed in the early 1970s by Shirato *et al.* [7] and by Haight *et al.* [8], which at that time were analyzed with theoretical models based on approximations of largely unknown accuracy, gave conflicting results for a_{nn}. Surprisingly, this discrepancy became even worse when Tornow *et al.* [6] reanalyzed the data using Monte Carlo simulations based on rigorous solutions of the 3N Faddeev equations with modern, realistic NN interactions. Perhaps more astonishing yet, even the data below the FSI peak, where the cross section does not depend on a_{nn}, could not be reproduced by the theory. Thus, although the experimentally well-established examples mentioned before are clearly pointing toward deficits in the theory, in the case of a_{nn} it is not clear whether the theory or some of the experiments, or both, might be to blame. For this reason, we have tried to contribute toward a possible solution of this problem by measuring the $n+d \rightarrow p+2n$ reaction again, using a very simple setup to obtain precise and reliable absolute cross-section data in the nn FSI peak.

II. EXPERIMENTAL DETAILS

The experiment was performed at the cyclotron of the Institut für Strahlen- und Kernphysik at the University of Bonn. The basic idea was to measure simultaneously both the protons and elastically scattered deuterons for the absolute normalization of the breakup cross-section data.

The neutron beam was produced via the ^{2}H(d, n)^{3}He reaction with 15-MeV deuterons incident on a 42-mm-long gas target, which was operated at room temperature at a pressure of 4.15 bar and closed with 10-μm-thick Havar foils. The beam was focused into the target by means of a circular, insulated 4-jaw Ta diaphragm with an aperture of 12 mm and stopped in a cooled gold disk close behind the target (see Fig. 1). The fraction of the beam hitting the slit system was typically less than 1%; from this the average beam diameter in the target was estimated to be (4 ± 1) mm full width at half maximum (FWHM). The whole target-beam stop assembly served as a

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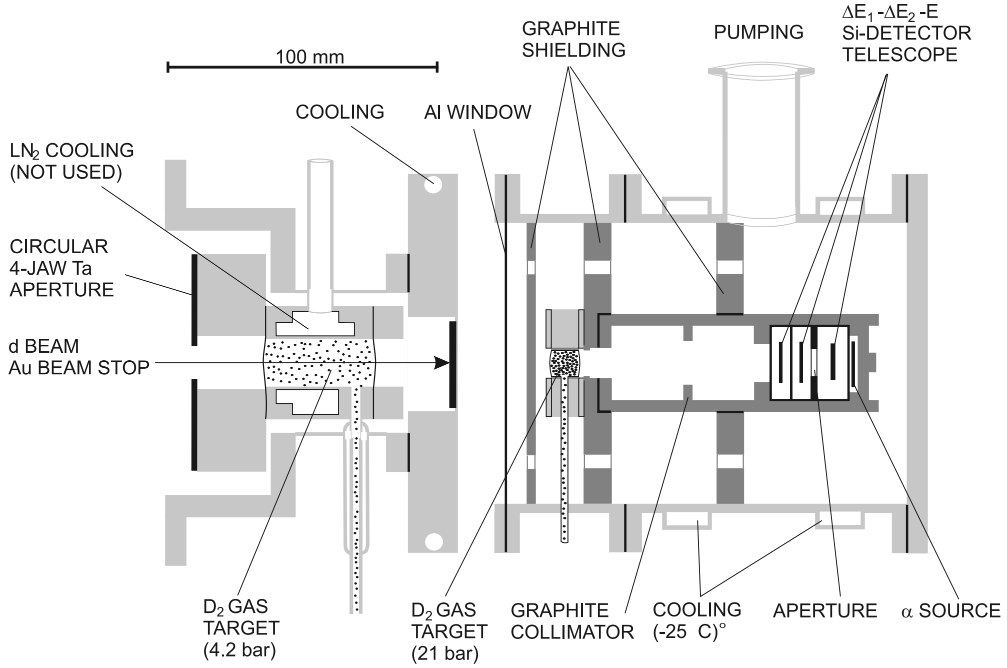

FIG. 1. Schematic drawing of the experimental setup. The neutrons were produced via the ^{2}H$(d,n)^3$He reaction in the gas target on the left. Graphite was used in the scattering chamber to shield the detectors from energetic charged particles originating from neutrons hitting the surrounding material.

Faraday cup, allowing for the relative normalization of the various data and background runs.

A 15-cm-long cylindrical reaction chamber, containing the scattering target and a detector telescope, was placed at 0° with respect to the deuteron beam directly behind the beam stop (Fig. 1). The target consisted of a 10-mm-long steel cylinder lined with graphite on the inside and had a diameter of 10 mm. It was closed at both ends with nominally 75-μm-thick Kapton foils and filled with deuterium gas at a pressure of 20.9 bar. Because of the bulging of the foils, their thickness was almost 30% smaller at the center, and the effective target length was 14.2 mm. Charged particles emitted in a cone around zero degrees were detected with a counter telescope consisting of three 150 mm^2 Si surface barrier detectors [9]: two ΔE detectors of 220 and 506 μm thickness, respectively, and a 1500-μm-thick E detector. The solid angle was defined by a circular 10-mm aperture between the last two detectors. The telescope was housed in a carbon collimator and shielded from all sides by graphite against neutron-induced charged-particle background. The last detector was irradiated from the back with α particles from a weak ^{241}Am source for monitoring of its performance during the measurements. The steel wall of the vacuum chamber was cooled to -25°C, resulting in a detector temperature of approximately -15°C, whereas the temperature of the target gas was -9°C. The distance from the center of the neutron production target to the center of the radiator, and from there to the aperture, was 90 and 91 mm, respectively. Under these geometrical conditions, the mean scattering angle of the detected protons was 4.9°.

At a typical deuteron beam intensity of 500 nA, the high-energy neutron flux in the monoenergetic peak from the ^{2}H$(d,n)^3$He reaction was $2.9\times10^6/(\mathrm{s}\times\mathrm{cm}^2)$ at the scattering target, with an average energy $E_n = 17.36$ MeV and an energy spread of 170 keV (FWHM). At the position of the Si detectors, i.e., about 18 cm from the neutron production target, the total flux, including the neutrons from the ^{2}H$(d,n)pd$ breakup reaction and from the beam stop, was roughly $2.7\times10^6/(\mathrm{s}\times\mathrm{cm}^2)$, resulting in an accumulated dose of $4.3\times10^{11}n/\mathrm{cm}^2$ in 45 h. This was about the limit at which the detector resolution began to deteriorate, and, moreover, their timing performance became worse. However, it was found that the useful lifetime of the detectors could be more than doubled by interrupting their exposure for a certain period of time when necessary to let them recover—normally during the night. In this way, their reverse current could be kept below 1 μA at all times, and it was possible to complete the whole experiment with just one set of detectors—a critical expense factor. Nevertheless, the pulse height of the E detector, e.g., decreased by 2.5% during the course of the experiment, so that individual runs had to be recalibrated before being added up.

The three detectors were operated in a conventional fast-slow coincidence. Their signals were recorded in list mode together with the time differences t_{12} and t_{13} between the ΔE_1 start detector and the ΔE_2 and E detector, respectively. After several test runs, the final measurement was performed within one week, in which about 50 h were used for the actual measurement, whereas during the rest of the time the detectors were regenerated. Five data runs, each one lasting about 4 h, were alternated with background runs in which the neutron production target and/or the scattering target were empty. At the end of each run, the position and width of the α line from the ^{241}Am source were measured and the reverse current of the detectors was determined to assure their operational integrity. In addition, one separate background run was taken at the end with the Kapton foils removed.

At free count rates of 6 kHz in ΔE_1, 17 kHz in ΔE_2, and 50 kHz in E—coming mostly from (n, p) and (n, α) reactions in the detectors—the number of accidental coincidences in the FSI peak region was about 3%.

III. DATA REDUCTION AND ANALYSIS

The raw data were first reduced by selecting either protons or deuterons by means of the two (E vs. ΔE) matrices, which allowed for a very clean particle separation. In addition, the (E vs. ΔE_1) matrix facilitated the removal of most of the background from Si(n, p) reactions. This background came from protons that were produced in the first ΔE detector and reached the E detector after traversing ΔE_2. Accidentals were removed via the matrix (t_{12} vs. t_{13}). Individual runs were then recalibrated, as explained above, using the prominent (n, p) peak from the hydrogen in the Kapton foils, and added together. Then E and ΔE were summed before finally the background, as determined from the properly normalized target-empty runs, was subtracted. This background was primarily caused by neutrons produced in the beam stop, by the remaining protons from (n, p) reactions in the ΔE_1 detector, and, to a lesser extent, by (n, p) scattering from traces of hydrogen on the inner surfaces of the carbon collimator. The two main background contributions are shown in Fig. 2 together with the uncorrected breakup data.

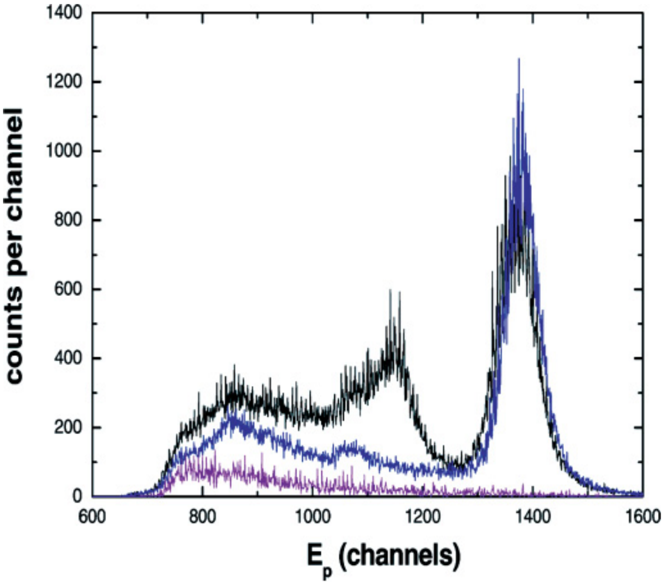

FIG. 2. (Color online) The three main kinds of proton spectra, after normalization. The prominent peak just below channel 1400 is due to elastic (n, p) scattering from the hydrogen in the target foils. Below the elastic peak, the upper curve shows the raw data, the curve in the middle is the radiator-empty run, and the lowest one represents the background measured with the neutron production target empty.

After the subtraction, however, the spectra were not yet background free. This could be seen from the runs taken with the scattering target empty: after removing all measured background, a small number of counts still remained in the channels below the elastic (n, p) peak. These counts were due to the presence of energy-degraded neutrons in the beam that were produced by multiple scattering in the bulk of the neutron production target and beam stop; a similar effect was also observed by Shirato *et al.* [7] and by Koori [10] in their experiments. The main contribution of these degraded neutrons came from their elastic scattering from the hydrogen in the Kapton foils and was therefore automatically subtracted with the target-empty runs. However, the *breakup* reactions induced by such neutrons could, of course, not be subtracted directly; this background had to be inferred from the number of degraded elastic counts in the radiator-empty runs. A corresponding correction was therefore applied to the breakup spectrum in an iterative way similar to the one described by Koori [10], starting from the degraded-neutron spectrum as deduced from the target-empty runs and taking into account the various elastic and breakup cross sections as a function of energy. This correction, which vanishes at the upper end of the breakup spectrum, grows toward lower energies; it was 2% across the FSI peak and reached 11% about 3 MeV below the peak.

The corrected data were analyzed by means of detailed Monte Carlo simulations, starting with the generation of the neutron beam in the production target and taking into account the finite geometry of the experimental setup as well as energy losses, the detector resolution, and energy and angle straggling. The energy scale was calibrated by means of the prominent peak of recoil protons from the hydrogen in the Kapton foils. To account for the additional energy smearing caused by the inhomogeneity of the convex Kapton foils—which was not included in the simulation—a Gaussian was added to the calculated resolution whose width was adjusted using the elastic (n, p) peak. The total energy resolution in the peak region was 450 keV.

The experimental breakup cross section $d^2\sigma_{np}/(d\Omega dE)$ was obtained via N_d, the yield for elastic (n, d) scattering, according to the relation

$$d^2\sigma_{np}/(d\Omega dE) = (N_p/dE) \times (d\sigma_{nd}/d\Omega)/N_d,$$

where (N_p/dE) is the number of breakup events per MeV, and $(d\sigma_{nd}/d\Omega)$ is the elastic (n, d) cross section. The (n, d) cross sections were calculated using the CD-Bonn potential [11]; a comparison with the results from several other realistic NN potentials showed that, in the angular and energy range relevant for this experiment, the differences were always smaller than 1%. Because N_p and N_d were measured simultaneously, most of the systematic experimental errors cancel out.

The point geometry breakup cross sections were obtained from rigorous, charge-dependent Faddeev-type calculations in momentum space with three different potentials as input for the NN interaction: the CD-Bonn potential [11], the Nijmegen potential Nijm I [12], and the Bonn-B potential [13]. The CD-Bonn and Nijm I interactions are charge dependent in the isospin $t = 1$ states, taking the difference in the $^1S_0$ force components of the nn and np subsystems explicitly into account. These potentials are "realistic" in that they describe the entirety of the NN data perfectly, with a normalized $\chi^2 \approx 1$. For the purpose of this analysis, modifications of the nn $^1S_0$ interaction were induced by adjusting one of the parameters in this partial wave, thus generating interactions for different nn scattering lengths. The Bonn-B potential is a one-boson-exchange momentum-space parametrization of the full Bonn potential [14], describing the world NN data with a less perfect normalized $\chi^2 \approx 2$. It is fitted in the $^1S_0$ state to the np scattering length; to get a set of nn $^1S_0$ interactions with particular values for a_{nn}, the procedure described in Ref. [15] was adopted where the $^1S_0$ interaction in Bonn-B was modified to reproduce the pp scattering length a_{pp}. This modification was accomplished by adjusting the σ-meson coupling constant $g_\sigma^2/4\pi$ [6]. The theoretical cross sections were incorporated into the Monte Carlo simulations to calculate absolute yields that could then be directly compared with the measured ones.

IV. RESULTS AND DISCUSSION

The results are shown in Fig. 3. The best fit to the data in the most sensitive part of the peak area, using the CD-Bonn NN potential, was obtained with a value of

$$a_{nn} = -16.52 \pm 0.69 \pm 0.52\,\text{fm},$$

where the first error gives the total statistical uncertainty, including background subtraction; the second one reflects the systematic error of the experiment, which is mainly due to the uncertainty in the corrections for the elastic (n, d) yield (±1%), in the normalization of the various background runs (±0.65%), and in the correction factor for the contributions from energy-degraded neutrons (±0.5%). The uncertainty in the theoretical value of the elastic (n, d) cross section is not included. The result is quite stable with respect to the actual range of data included in the fit. For example, it changes to $a_{nn} = -16.81 \pm 0.63 \pm 0.62$ fm if the 15 data points between 13.5 and 15.0 MeV are used.[1]

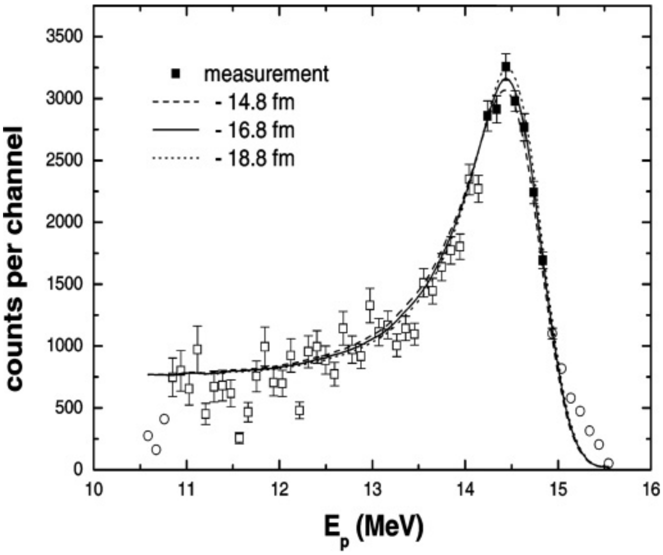

FIG. 3. Final proton spectrum of the $n+d \rightarrow p+2n$ reaction at $E_n = 17.36$ MeV, in comparison with the Monte Carlo simulations using CD-Bonn, for three values of the nn scattering length. The full squares were used in the fit to extract a_{nn}. The data above 15 MeV, denoted by open circles, are probably still contaminated by background from the tail of the elastic (n, p) peak, which cannot be accurately subtracted because of its slightly different width and position in the target-full and target-empty runs, respectively. Below 10.8 MeV, the ΔE detectors are beginning to stop the protons, thereby cutting the spectrum off.

Looking at Fig. 3, one can see that, first of all, the agreement between theory and experiment in the low-energy *tail* of the FSI peak, where the cross section becomes independent of a_{nn}, is quite good; here we find that the theory is higher by $(3.7 \pm 5.2)\%$. This is in remarkable contrast to most previous such experiments (see Ref. [6]), where typically differences of up to 20% were reported. (It might be noted that the large scatter of some of the data points in the flat tail of the peak, where the background was rather high, is an artifact produced by the extensive data manipulation, in particular the recalibration and rebinning of the data before individual runs could be added or subtracted. However, it is of no concern as long as one is interested only in the average over a larger energy range.)

In the peak area, one notes the rather low sensitivity of the cross section with respect to a_{nn}. This is, of course, to some extent due to our extended geometry and moderate experimental resolution. However, even for ideal point geometry, the sensitivity of inclusive n-d breakup measurements is generally at least a factor of 2 smaller than for kinematically complete ones—which would normally more than compensate for the intrinsically smaller count rate of coincidence experiments. Figure 3 also shows that already about 300 keV below the peak the sensitivity vanishes and changes sign below that point—unlike in complete experiments. About 3 MeV below the peak the sensitivity runs out completely.

The authors of Ref. [6] have reported changes in the peak cross section of several percentages for different NN potentials, especially when the predictions of older NN models such as Nijmegen [16], Paris [17], or AV14 [18] were used in the three-body calculations instead of Bonn-B. It was concluded that these discrepancies were most likely due to the on-shell differences between the potentials, whereas off-shell differences probably have only a small influence on the cross section. The differences between Bonn-B and the more recent models Nijm I and Nijm II [12] were found to be much smaller. The authors concluded that, at least below $E_n = 20$ MeV, the theoretical uncertainty in the extraction of a_{nn} from kinematically incomplete experiments is about 0.4 fm, although a systematic search of a_{nn} with different potentials has not been made.

To further elucidate this point, we have fitted our data also with Nijm I and Bonn-B. Using the data as indicated in Fig. 3, and quoting only the statistical errors, the results were $a_{nn} = -16.25 \pm 0.64$ fm and $a_{nn} = -15.98 \pm 0.64$ fm,

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[1] Individually, starting from the left, the seven full data points in Fig. 3 give a_{nn} values of -19.2 ± 11.4, -11.6 ± 4.0, -19.1 ± 2.4, -15.6 ± 1.5, -17.0 ± 1.7, -16.2 ± 1.5, and -17.0 ± 1.3 fm, respectively.

respectively. This confirms that the theoretical uncertainty is indeed very small as long as truly realistic, phase-shift equivalent NN potentials such as CD-Bonn or Nijm I are used in the 3N calculations. However, it has long been known [19] that in kinematically *complete* measurements, for certain production angles of the nn pair the cross section in the FSI peak becomes practically independent of the particular NN potential and also does not depend on the possible action of the two-π-exchange three-nucleon force, thereby removing this uncertainty almost completely. In addition, the background problems are generally less severe in coincidence measurements. Together with their higher sensitivity, this clearly speaks in favor of kinematically complete experiments for any high-precision determination of a_{nn}.

V. SUMMARY

The nn FSI was investigated in the ^{2}H$(n, p)2n$ reaction in kinematically incomplete geometry at 17.36 MeV. Detecting the breakup protons emitted at an average angle of 4.9°, absolute cross-section data were determined via elastic (n, d) scattering, which was measured simultaneously. The data were analyzed with detailed Monte Carlo simulations based on rigorous three-body calculations, using for the nucleon-nucleon interaction the two high-quality NN potential models CD-Bonn and Nijm I, respectively, as well as the somewhat less realistic Bonn-B potential. The absolute yield of the breakup spectrum is reproduced very well over the entire energy range investigated, unlike in most previous such experiments. With CD-Bonn, the value of the nn scattering length deduced from the cross section in the FSI peak was $a_{nn} = -16.5\pm0.9$ fm, whereas Nijm I gave -16.3 ± 0.8 fm and Bonn-B -16.0 ± 0.8 fm, where the errors indicate the combined statistical and systematic uncertainty. It is concluded that the theoretical uncertainty in the extraction of a_{nn} from kinematically incomplete experiments is probably very small—as long as truly realistic NN potentials are used. However, despite the intrinsically lower count rate of kinematically *complete* experiments, their significantly higher sensitivity, together with their smaller background problems and the even lesser theoretical uncertainty, makes them a better choice for the high-precision determination of a_{nn}.

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