New Attempt to Determine the n-n Scattering Length with the ^{2}H$(n, np)n$ Reaction

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The n-n final-state interaction (FSI) was investigated via the ^{2}H$(n, np)n$ reaction at 25 MeV, using a geometry which enables the simultaneous observation of n-p quasifree (QFS) scattering. The data were analyzed with Monte Carlo simulations based on rigorous Faddeev calculations with realistic nucleon-nucleon potentials. The value of a_{nn} deduced from the absolute yield in the FSI peak is -16.27 ± 0.40 fm while the relative data, normalized in the QFS region, give -16.06 ± 0.35 fm. Thus our results differ from the "recommended" value of $a_{nn} = -18.5 \pm 0.3$ fm by more than 5 standard deviations.

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The $^1S_0$ nucleon-nucleon scattering lengths a_{NN} are fundamental observables for the theoretical understanding of nuclear forces, the difference between the nuclear part of the neutron-neutron and proton-proton scattering length being a direct measure of charge symmetry breaking. Both a_{nn} and a_{pp} have large negative values compared with typical length scales in nuclear physics, leading to a strong magnifying effect which translates a small variation in the strength of the NN potential into a large change of a_{NN}.

Lacking free neutron targets, the n-n scattering length can be measured only via breakup reactions with two neutrons in the final state. Indeed, numerous attempts [1,2] have been made to determine a_{nn}, using mostly the ^{2}H$(\pi^-, \gamma n)n$ and ^{2}H$(n, nn)p$ reactions and investigating the n-n final-state interaction (FSI), i.e., the region of phase space where the two neutrons travel together with low relative energy. While the ^{2}H$(\pi^-, \gamma n)n$ reaction soon suggested for a_{nn} a value around -18.5 fm, the results from n-d breakup experiments could not be taken seriously until rigorous, fully charge-dependent three-body calculations [3] with modern, realistic NN potentials [4–6] became feasible. But even then a remaining problem was the possible influence of three-nucleon ($3N$) forces, whose theoretical foundation is still in its infancy. However, recent investigations [7] based on the Tucson-Melbourne 2π-exchange $3N$ force [8] revealed that n-d breakup cross sections in the FSI configuration are little influenced by the action of such $3N$ forces. In addition, it was found [9] that, in kinematically complete experiments, the influence of $3N$ forces appears to vanish completely for specific production angles of the n-n pair. This insight now made n-d experiments, performed at these angles, especially promising because they should, in principle, enable a virtually model-independent determination of a_{nn}. A first experiment of this kind, at $E_0 = 13$ MeV, was described recently [7]. In this Letter we report on a similar investigation, done at $E_0 = 25.3$ MeV, and employing a different geometry.

In most previous n-d experiments a thick, active target was used and the two neutrons were detected with two scintillators positioned at (nearly) the same angle on one side of the beam. This provides a clean kinematical condition for the observation of the n-n FSI but produces strong cross talk between the detectors. In the present experiment, this problem was avoided by detecting only one of the neutrons in coincidence with the recoiling proton on the other side of the beam. Although this mandated the use of a thin target, the smaller target thickness was partly compensated by a higher n-beam intensity and by the higher efficiency of the proton detector. Also, there were no losses from neutron multiple scattering. The main advantage of this geometry, however, is the simultaneous observation of quasifree n-p scattering (QFS) where the cross section is practically independent of a_{nn}. Thus the n-p QFS region provides a convenient, built-in normalization for the n-n FSI peak.

The experiment was performed at the cyclotron of the Institut für Strahlen- und Kernphysik at the University of Bonn. A plan view of the experimental layout is shown in Fig. 1. A quasimonoenergetic neutron beam was produced via the ^{2}H$(d, n)^3$He reaction with 26.9 MeV deuterons incident on a liquid-nitrogen cooled gas target operated at a pressure of 39 bars. The primary beam was stopped directly behind the gas target which served as a Faraday cup. The neutrons were collimated at 0° to form a well-defined [10] circular beam with a diameter of 31 mm at the reaction target. With a deuteron beam intensity of 900 nA, the neutron flux at the target in the high-energy (HE) peak from the ^{2}H$(d, n)^3$He reaction was 1.4×10^6 s^{-1}, with an average energy $E_0 = 25.3$ MeV and an energy spread $\Delta E_0 = 4.0$ MeV. The HE neutrons were separated from the breakup continuum via their time of flight. As a beam monitor, a double proton recoil telescope (PRT) was placed in the n beam to detect protons emitted from a CH_2 target at angles of $\pm 35°$. The PRT was essential for the absolute normalization of the neutron beam as will be discussed later on.

Neutrons were detected at $\Theta_n = 55.5°$ and protons at $\Theta_p = 41.15°$, with $\Phi_{np} = 180°$; these are the angles at which the model dependence of the breakup cross section vanishes [9]. Since the n-n FSI occurs at proton energies above 15 MeV and runs parallel to the E_n axis, a rather thick target could be used nevertheless; by projecting the

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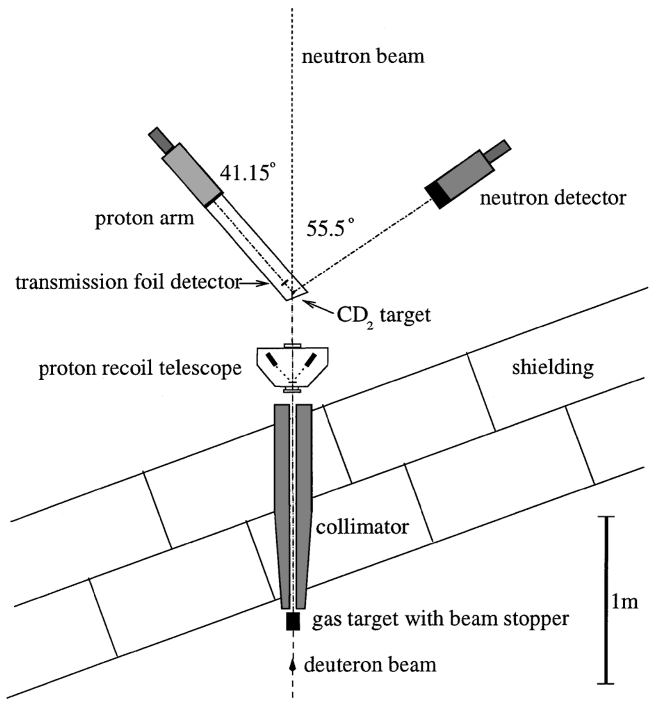

FIG. 1. Schematic drawing of the experimental setup, approximately to scale.

n-p coincidences onto the E_n axis, the energy smearing in the proton arm does not affect the FSI peak. The target consisted of a 48 mg/cm^2 CD_2 foil, suspended in the beam by means of two thin Be wires. At the target position, the n beam had a plateau of constant intensity with a diameter of 25 mm, and illuminated the whole target homogeneously. At 8 cm from the target a scintillator foil of 5 mg/cm^2 thickness was positioned in an Al reflector with very thin windows, viewed from above by a photomultiplier. The signals produced in this transmission foil detector (TFD) served as start signals for all time-of-flight (TOF) measurements. The protons were detected 70 cm from the target with a plastic-scintillator disk of 10 cm diameter. The target and TFD were mounted in an evacuated pipe, called "proton arm," which was equipped with a Be entrance window and a Ti exit foil for the n beam, and closed at the end by the proton detector. The n detector consisted of a standard BA1 cell filled with NE213 liquid scintillator, with a diameter of 5 in. and a thickness of 3 in., and was equipped with n-γ pulse-shape discrimination. All detectors had LED pulsers to monitor gain shifts, pileup, and dead times.

The neutron fluence F_n was determined very accurately by means of n-p scattering. For this, the CD_2 target was replaced by a CH_2 foil of equal size. The number of neutrons/cm^2 at the target could then be calculated from the number of recoil protons, with the PRT serving as a relative monitor for the subsequent measurements with the CD_2 target. The total error in F_n is $\pm1.1\%$. The efficiency of the TFD, measured with the same setup, was found to be $\geq 99.9\%$.

A special effort went into the determination of the n-detector efficiency. In a first step, the *central* efficiency was measured, using again the setup with the CH_2 target. The n detector was positioned at 90° with respect to the proton arm, close to the target to assure that all n-p neutrons hit the detector near its center. The free count rate was adjusted to be the same as in the n-d experiment so that the efficiency was measured under conditions matching those in the breakup experiment. The whole spectrum of beam neutrons was used; thus the efficiency could be determined simultaneously for all energies between $E_n = 2.7$ and 11 MeV. Windows were set off-line in the TOF spectrum to select bins of energies for the scattered neutrons for which the efficiency was determined from the number of free proton counts vs the number of p-n coincidences. Since it was a relative measurement, the error is mainly due to statistics. The measured central efficiencies were compared to Monte Carlo calculations based on an expanded version [11] of the PTB program of Dietze and Klein [12]. The difference between experiment and simulation was $(0.2 \pm 0.9)\%$, and there is no energy dependence of this difference. The PTB program was then employed to calculate the *average* efficiency ε which, for our setup, was 3.8% smaller than the central one. We estimate that the additional error in ε, coming mainly from the uncertainties in the cross sections for in-scattering from the detector housing, is less than 1%; hence we know the efficiency of our n detector within $\pm1.4\%$. The PTB program also provided the radial dependence of ε.

For the breakup experiment, the event trigger signal was generated by a fast coincidence between the TFD, the p detector, and the n detector. In addition, twofold coincidences were recorded between the ΔE and E detectors of the PRT. The trigger signals from the LED pulser driver were counted with a scaler and used to create a separate gate. The singles count rates were 2 kHz in the TFD, 10 kHz in the p detector, and 85 kHz in the n detector. The total effective running time was 400 hours. More details will be given in an upcoming paper [13].

The raw data were reduced by eliminating events from the breakup continuum of the n beam and by setting a lower threshold of 60 keV in the n detector. The pulse shape was utilized to get rid of coincidences with γ rays. Deuterons in the p detector were removed by a window in the (E_p vs TOF_p)-matrix. The remaining background, being accidental, was subtracted after projection onto the TOF_n axis. Some corrections had to be applied to the reduced data prior to comparison with theory. Long-time gain changes and shifts of the time-zero points were corrected by means of the pulser peaks. All other distorting effects were included in the Monte Carlo simulation of the experiment. Of these, the most important one was the efficiency of the n detector whose r dependence was taken into account explicitly. Besides the finite geometry, other effects included the energy spread of the beam, time resolution, straggling and energy loss of the protons, and the small loss of neutrons due to scattering. Owing to the high count rate in the n detector, there was a certain probability for any TOF event in the neutron arm to be stopped early by an accidental count, thus leading to an apparent loss of true coincidences. Based on the measured distribution of the pulser counts along the TOF_n axis, the exact magnitude of the necessary corrections was calculated for each event. The number of pulser coincidences also determined the dead time losses which amounted to 1.8%. A more significant correction was required because of the special geometry of this experiment: since the neutron detector was positioned on the recoil axis of the $2n$ system with zero relative energy, there was a considerable probability for *both* FSI neutrons to hit the detector. This increased the detection efficiency and also distorted the TOF_n spectrum to some extent. However, being a purely kinematical effect, its consequences can be calculated very accurately, and they were included in the simulation for each value of a_{nn}. The resulting additional error in the simulated count rates is not more than 0.3%. There are few double hits in the QFS peak.

The Monte Carlo simulation of the experiment was based on absolute theoretical cross sections computed for different values of a_{nn}. To this end rigorous, fully charge-dependent Faddeev calculations in momentum space [3] were performed, using the CD-Bonn potential [6] as input for the NN interactions. Point-geometry cross-section libraries were generated for energies from 21 to 29 MeV in steps of 0.5 MeV, and for values of a_{nn} between -15 and -20 fm in steps of 1 fm. The changes in a_{nn} were induced by modifying the strength of the $^1S_0$ force in the CD-Bonn potential. For each simulated event, the cross section was interpolated from these libraries and incorporated in the Monte Carlo simulation.

The final data are shown in Fig. 2 after conversion of the neutron TOF into energy and projection onto the E_n axis; a threshold of 6 MeV has been applied in E_p. Included are the finite-geometry Monte Carlo spectra calculated with $a_{nn} = -15$, -16.3, and -18 fm. Clearly, the theory reproduces the data very well in the region of n-p QFS where both the measured shape and the absolute number of counts agree nicely with the calculations. To extract the n-n scattering length, a minimum $-\chi^2$ fit was made to the FSI peak, resulting in a value of

$$a_{nn} = -16.27 \pm 0.40 \text{ fm}.$$

For this fit, the absolute yield in the region between $E_n = 1.5$ and 4.5 MeV was compared with the Monte Carlo predictions for different values of a_{nn}. The range of comparison was optimized for maximum sensitivity with regard to a_{nn}. The best fit, with $\chi^2_{\min} = 1.15$, was obtained when the simulated spectra were shifted by 70 keV with respect to the measured one, the reason being an imperfect walk correction in TOF_n. However, the change in a_{nn} caused by this shift is only 0.03 fm. The influence of various experimental uncertainties was also investigated by means of Monte Carlo simulations. The total uncertainty of ± 0.40 fm consists to about equal parts of statistical and systematic errors, added quadratically.

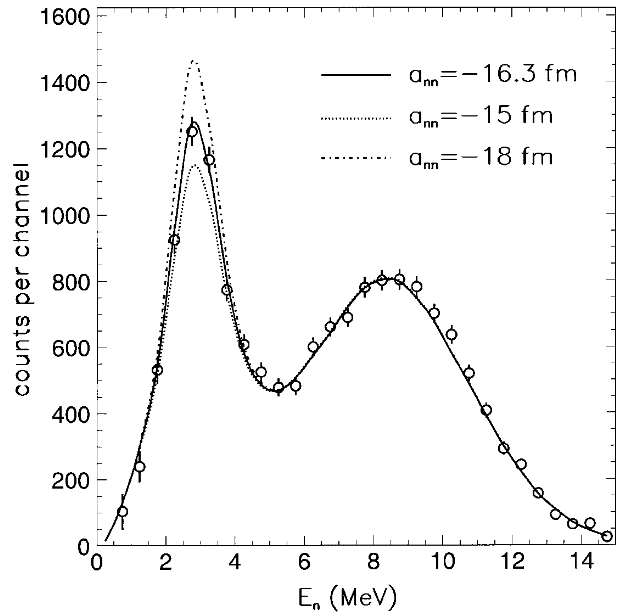

FIG. 2. The data (circles with error bars) after conversion of the neutron TOF into energy and projection onto the E_n axis, together with the finite-geometry Monte Carlo predictions for three values of the n-n scattering length. The peak at $E_n = 2.8$ MeV is due to the n-n FSI; the broader one at higher energies comes from n-p QFS.

Because the cross section in the region of n-p QFS is independent of a_{nn}, we can also normalize the FSI peak there. Using for this the data between $E_n = 5$ and 12 MeV, the normalization factor is 0.984 ± 0.012. Performing the analysis with the data between 1.5 and 4.5 MeV renormalized in this way, we obtained

$$a_{nn} = -16.06 \pm 0.35 \text{ fm}.$$

Of course, since the normalization factor is close to 1, this value for a_{nn} does not differ much from the one obtained by fitting the absolute yield. However, the sources of errors for the two results are quite different, the latter one being almost completely due to statistics while most of the systematic errors have canceled out.

The outcome of this experiment is disturbing. Our results for a_{nn} clearly disagree with the findings of Ref. [7] which were $a_{nn} = -18.7 \pm 0.6$ fm. The results of these two experiments differ by almost 4 standard deviations. Our results are also at variance with the "recommended" value from the $^2\mathrm{H}(\pi^-, \gamma n)n$ reaction [1,2], which in turn agrees with Ref. [7]. On the other hand, the two values obtained from the present experiment agree nicely with each other, and it should be emphasized once more that they represent two largely independent results because most of the systematic errors have canceled out in the second one. This makes it unlikely that our results are spurious because of systematic errors. Our results also agree with those of all other kinematically complete n-induced breakup experiments (which cannot be dismissed, as Glöckle *et al.* have shown [3], even though they were obtained with less sophisticated theoretical models). Neither the inclusion of the Tucson-Melbourne $3N$ force [8] nor the use of different NN potentials [4,5] in the Faddeev calculations produces noticeably different results. One difference between our experiment and that of Ref. [7]—apart from the higher energy—is the different geometry. While in Ref. [7] the two final-state neutrons were detected, in the present experiment coincidences between one of the neutrons and the recoiling proton were recorded. Although it is not easy to see why this should lead to different results, it is interesting to note that the cross sections for the two geometries—at the same energy and production angle for the n-n pair—differ by a factor of 4, showing that the breakup amplitudes are very different indeed. In summary, it must be concluded that the long-standing controversy regarding the determination of a_{nn} via the $n + d$ reaction has not been resolved but renewed. At present, no explanation is available, and further experimental studies are certainly needed. The results of three additional n-d breakup experiments, aimed at the investigation of the well-known neutron-proton FSI to serve as a consistency check, and also at n-n and n-p QFS, will be published shortly [13,14].

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[1] I. Šlaus, Y. Akaishi, and H. Tanaka, Phys. Rep. **173**, 259 (1989).
[2] C. R. Howell *et al.,* Phys. Lett. B **444**, 252 (1998).
[3] H. Witała, Th. Cornelius, and W. Glöckle, Few-Body Syst. **3**, 123 (1988); H. Witała, W. Glöckle, and Th. Cornelius, Phys. Rev. C **39**, 384 (1989); W. Glöckle, H. Witała, D. Hüber, H. Kamada, and J. Golak, Phys. Rep. **274**, 107 (1996).
[4] V. G. J. Stoks *et al.,* Phys. Rev. C **49**, 2950 (1994).
[5] R. B. Wiringa, V. G. J. Stoks, and R. Schiavilla, Phys. Rev. C **51**, 38 (1995).
[6] R. Machleidt, F. Sammarruca, and Y. Song, Phys. Rev. C **53**, 1483 (1996).
[7] D. E. Gonzáles Trotter *et al.,* Phys. Rev. Lett. **83**, 3788 (1999).
[8] S. A. Coon *et al.,* Nucl. Phys. **A317**, 242 (1979); S. A. Coon and W. Glöckle, Phys. Rev. C **23**, 1790 (1981).
[9] H. Witała, D. Hüber, W. Glöckle, W. Tornow, and D. E. González Trotter, Few-Body Syst. **20**, 81 (1996).
[10] M. Hohlweck, T. Köble, F. Meyer, M. Ockenfels, J. Weltz, and W. von Witsch, Nucl. Instrum. Methods Phys. Res., Sect. A **281**, 277 (1989).
[11] I. Fabry, Diplom thesis, University of Bonn, 1998 (unpublished).
[12] G. Dietze and H. Klein, Nucl. Instrum. Methods Phys. Res. **193**, 549 (1982).
[13] V. Huhn *et al.* (to be published).
[14] A. Siepe *et al.* (to be published).