New measurement of the neutron-proton scattering length a_{np} via the *n-d* breakup reaction at 25 MeV

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The $^1S_0$ *n-p* scattering length a_{np} has been measured using the *n-d* breakup reaction at 25 MeV. The experiment was performed in a geometry where the neutron and proton were detected in coincidence at the same angle. The data were analyzed with rigorous three-nucleon calculations using realistic nucleon-nucleon potentials. The result of $a_{np} = -24.3 \pm 1.1$ fm agrees with the well-known value from free *n-p* scattering, and also with previous results from *n-d* breakup experiments which were performed in different geometries.

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The *n-d* breakup reaction provides one of the few means available for the investigation of the elusive neutron-neutron interaction. Since free neutron targets are not on hand, either *n-n* quasifree scattering (QFS) or the final-state interaction (FSI) must be employed, using systems with at least three particles in the final state. Since rigorous three-nucleon calculations [1] with realistic nucleon-nucleon potentials [2–4] have become feasible, the *n-d* breakup is, along with the $^2H(\pi^-,nn)\gamma$ reaction, the most obvious choice; in both cases, only three hadrons are involved, and there is no Coulomb interaction.

The *n-n* FSI in the $^2H(n,nn)p$ reaction has been investigated in two recent experiments [5,6] in order to extract a_{nn}, the $^1S_0$ neutron-neutron scattering length. In the two measurements, which were performed at 13.0 and 25.3 MeV, respectively, different geometries were used: while in Ref. [5] the two neutrons were detected in coincidence at the same angle (''final-state geometry''), in our own measurement [6] only one of the neutrons was detected together with the recoiling proton on the other side of the beam (''recoil geometry''). Although, of course, the experimental technique should not affect the outcome of the experiment, the two results were clearly contradictory, differing by almost four standard deviations.

It has long been argued that a natural way to test the reliability of the method used for extracting a_{nn} would be to measure a_{np}, the well-known neutron-proton scattering length in the $^1S_0$ state, using the same reaction. This has been done in both investigations [5,6], and in each case the result agreed perfectly with the value known from free *n-p* scattering. In both cases a_{np} was measured in recoil geometry. In this paper, we report on a further measurement of a_{np} which, for the first time, was performed in final-state geometry, thus completing our tests for the suitability of the *n-d* breakup reaction for the determination of a_{nn}.

The experiment was performed at the cyclotron of the Institut für Strahlen und Kernphysik at Bonn University. A quasimonoenergetic neutron beam was produced *via* the $^2H(d,n)^3He$ reaction with 26.7-MeV deuterons incident on a liquid-nitrogen-cooled gas target operated at a pressure of 38 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 circular beam with a diameter of 31 mm (full width at half maximum) at the reaction target. With a deuteron beam intensity of 2.5 μA, the neutron flux at the target in the high-energy (HE) peak from the $^2H(d,n)^3He$ reaction was 3.3×10^6/s, with an average energy $E_0 = 25.1$ MeV and an energy spread $\Delta E_0 = 3.4$ 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 $\pm35°$. The PRT allowed the determination of the neutron fluence with an accuracy of 1.1% [6].

Neutrons and protons were detected in coincidence at $\Theta_n = \Theta_p = 32°$ and $\Phi_{np} = 0°$. The *n* detector consisted of a standard BA1 cell filled with NE213 liquid scintillator, had a diameter of 5 in. and a thickness of 3 in., and was equipped with *n-*γ pulse-shaped discrimination. Its efficiency, including the effect of pileup, was known from previous measurements [6] to better than $\pm1.4\%$. The protons were detected with a 1.5-mm-thick 450-mm^2 Si surface barrier detector which was collimated with a circular Ta slit of 20 mm diameter. So as to achieve the highest accuracy within the limited available time, the tightest possible geometry had to be chosen without losing too much sensitivity with regard to a_{np}. Monte Carlo simulations showed that the best compromise to this end was to position the front face of the *n* detector at 43 cm from the target, and the slit of the *p* detector at 10.2 cm. All detectors were provided with pulser signals to monitor gain shifts, pileup, and dead time. The *p* detector provided the start signal for all time-of-flight (TOF) measurements.

The target consisted of a 21-mg/cm^2-thick CD_2 foil, facing the detectors. It had the shape of an upright ellipse with half-axes of 12 and 10 mm, respectively, and was suspended by means of two thin Be wires inside the intensity plateau of the *n* beam, which had a diameter of 25 mm at the target position. Due to the danger of fatal background from in-

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scattered neutrons, it was not possible to use a conventional scattering chamber. Therefore, no chamber was used at all, and the *p* detector was operated under normal pressure. However, in order to reduce the energy loss of the protons, the target and the *p* detector were covered with a thin plastic bag in which most of the air was replaced by He, which continuously flowed into the bag from below.

For the measurement of a_{np}, the trigger signal was generated by a fast coincidence between the *p* and *n* detector. For each trigger, six parameters were written to disc in list mode: the dynode signal as well as (for pulse-shape discrimination purposes) the long and short components of the anode signal from the *n* detector, the pulse height of the *p* detector, and the TOF's between the *n* and *p* detector (TOF_{np}), and between the *p* detector and the rf of the cyclotron (TOF_C). In addition, twofold coincidences were recorded between the ΔE and E detectors of the PRT. The trigger signals from the pulser were counted with a scalar and used to create a separate gate. The total running time was 240 h. The singles count rates were 110 kHz in the *n* detector with a discriminator threshold corresponding to 130 keV electron energy, and 250 Hz in the *p* detector. A background run was made with the CD_2 target replaced by a ^{12}C target of equal thickness in order to investigate possible contributions from carbon and from the residual air in and around the He bag.

The raw data were first reduced by selecting the HE part of the *n* beam via TOF_C, and by getting rid of most of the γ signals in the *n* detector using the pulse-shape matrix. Next, a threshold of 1 MeV electron energy was set in the dynode spectrum of the *n* detector, and of 3 MeV in the *p* detector. Then the accidental background was subtracted by means of TOF_{np}, and also the normalized "true" background from the background run. The data were then projected onto the E_p axis for comparison with the theoretical predictions. The experiment was simulated in detail with Monte Carlo (MC) calculations [6]. The main effects to be taken into account included the extended geometry, the efficiency of the *n* detector, and the energy loss of the protons. Also incorporated was the loss of neutrons due to scattering in the *p* detector, which amounted to around 6.5%.

Absolute theoretical spectra were produced with breakup cross sections obtained from rigorous, fully charge-dependent Faddeev-type calculations in momentum space using the CD-Bonn potential [2] as input for the nucleon-nucleon interaction. A detailed description of the theoretical formulation and numerical procedure can be found in Ref. [1] and will not be repeated here. For the purpose of this analysis, modifications of the *n-p* $^1S_0$ interaction were induced by adjusting one of the parameters for the fictitious σ boson in this partial wave [7], thus generating interactions with different *n-p* scattering lengths. For these, large arrays of point-geometry cross sections were calculated for energies from 23 to 28 MeV in steps of 0.5 MeV, and stored in the computer. For each simulated event, the cross section was interpolated from this library and incorporated into the MC routine [8].

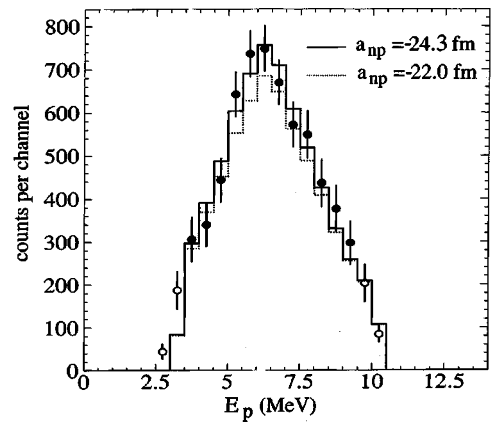

FIG. 1. The final data (dots with statistical errors), after projection onto the E_p axis, together with the finite-geometry Monte Carlo predictions for $a_{np}=-22.0$ and -24.3 fm (histograms). The data denoted by open symbols were not used for the analysis.

The final data, projected onto the proton energy axis, are shown in Fig. 1 (dots with error bars), together with the finite-geometry Monte Carlo predictions calculated with $a_{np}=-22.0$ and -24.3 fm, respectively. In order to extract the *n-p* scattering length, a minimum-χ^2 fit was made, which resulted in a value of

$$a_{np}=-24.3\pm 1.1 \text{ fm}.$$

For this fit, the absolute yield in the region between $E_p=3.5$ and 9.5 MeV was compared with the MC predictions for different values of a_{np}. The range of comparison was optimized for maximum sensitivity with regard to a_{np}. The data points at the highest proton energies were excluded because their neutron energies are close to the threshold of the *n* detector. The error of ± 1.1 fm is mostly due to statistics. As can be seen from Fig. 1, the shape of the peak, which is strongly influenced by the finite geometry and by the proton energy loss, is reproduced very well by the MC simulation.

The present result for a_{np}, which was obtained in final-state geometry, agrees perfectly with those from earlier experiments, performed in recoil geometry, namely, -23.5 ± 0.8 fm [5] and -23.9 ± 1.0 fm [6], respectively. They all agree with the value of -23.748 ± 0.009 fm deduced from free *n-p* scattering [9]. This shows that—as it should be—the geometry of the measurement does not affect the result for the *n-p* scattering length. One would think that the same holds true for a_{nn}.

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[1] W. Glöckle, H. Witała, D. Hüber, H. Kamada, and J. Golak, Phys. Rep. **274**, 107 (1996).
[2] R. Machleidt, F. Sammarruca, and Y. Song, Phys. Rev. C **53**, 1483 (1996).
[3] R. B. Wiringa, V. G. J. Stoks, and R. Schiavilla, Phys. Rev. C **51**, 38 (1995).
[4] V. G. J. Stoks, R. A. M. Klomp, C. P. F. Terheggen, and J. J. de Swart, Phys. Rev. C **49**, 2950 (1994).
[5] D. E. Gonzáles Trotter, F. Salinas, Q. Chen, A. S. Crowell, W. Glöckle, C. R. Howell, C. D. Roper, D. Schmidt, I. Šlaus, H. Tang, W. Tornow, R. L. Walter, H. Witala, and Z. Zhou, Phys. Rev. Lett. **83**, 3788 (1999).
[6] V. Huhn, L. Wätzold, Ch. Weber, A. Siepe, W. von Witsch, H. Witala, and W. Glöckle, Phys. Rev. C **63**, 014003 (2001).
[7] R. Machleidt, Adv. Nucl. Phys. **19**, 189 (1989).
[8] L. Wätzold, Ph.D. thesis, University of Bonn, 2000.
[9] L. Koester and W. Nistler, Z. Phys. A **272**, 189 (1975).