Neutron-Neutron $^1S_0$ Scattering Parameters from a Kinematically Complete Experiment on the Reaction $^2H(n, 2n)H$

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(Received 17 April 1972)

In a complete experiment on the reaction $^2H(n, 2n)H$ we have observed neutron-neutron and neutron-proton final-state interactions. The analysis by a three-body calculation with separable potentials gives $a_{nn} = -14.5 \pm 0.8$ fm for the $^1S_0$ neutron-neutron scattering length and $r_{nn} = 2.7 \pm 0.5$ fm for the effective range.

During the last years several experiments have been performed on three-particle reactions with two neutrons in the final state. The commonly used formalism to extract the $^1S_0$ neutron-neutron scattering length was that of the simple Watson-Migdal approximation.[1] However, the only information from this model is the relative dependence of the breakup amplitude on the internal energy of a single two-particle subsystem, which is assumed to dominate the final state. Now exact three-body calculations with separable potentials using integral equations of the Faddeev type are available.[2,3] These calculations include all the coherent and incoherent breakup amplitudes. Contrary to the Watson-Migdal model, the three-body calculations also give absolute values of the cross section. The results of the kinematically complete measurement on the reaction $^2H(n, 2n)H$ presented here were analyzed by both the three-body calculations described in Ref. 3 and the Watson-Migdal approximation.[4]

The experiment was performed to improve earlier results from the same reaction[5] and to observe simultaneously the neutron-neutron and neutron-proton pairs at low relative energies in the final state. This procedure allows the simultaneous fit to the ratio of the two differential cross sections and to the energy dependence of these along the kinematically allowed curves. The advantage of this method is that only ratios of neutron cross sections are needed which in simultaneous measurements can be determined with much higher precision than absolute values. Though the cross section is actually produced by many coherent amplitudes, in this paper we still use the language of the Watson-Migdal model in order to distinguish between different kinematical situations in the final states.

The experimental arrangement is shown in Fig. 1. A target of C_6D_6 was bombarded with 18.4-MeV neutrons. This target, labeled *DO* (4×4 cm, NE 230), served simultaneously as a fast scintillator. The scintillation caused by the proton from deuteron breakup gave the start signal for three neutron time-of-flight spectrometers and the proton energy as an additional kinematic constraint. The stop signals came from the neutron detectors *DA*, *DB*, and *DC*, respectively (Ne 213, 7.5 cm long, 10 cm diam each).

Three triple-coincident spectra were obtained. *DO-DA-DB* coincidences correspond to the strong neutron-neutron final-state interaction because of the small internal energy of the *n-n* pair. *DO-DA-DC* and *DO-DB-DC* coincidences correspond to the strong neutron-proton final-state interaction because of the small internal energy of the *n-p* pair at nearly identical kinematic conditions. The maximum enhancement from the *n-n* final-state interaction would be obtained by choosing equal azimuthal angles $\varphi_A = \varphi_B$ besides $\theta_A = \theta_B$. However, this would require the detectors *DA* and *DB* to be placed behind one another without protective shielding. The curves of relative energies between the particles strongly interacting in the final state, E_{nn} and E_{np}, show minima which extend down to about 40 keV.

The experiment was performed on line with a PDP-9 computer. Within 6 weeks of measuring time a total of 2800 true *n-n* and 840 true *n-p* events were collected. Figure 2 shows the two-dimensional neutron time-of-flight spectrum which was obtained for the case of the strong neutron-neutron final-state interaction (*DO-DA-DB* coincidences). We only present events where the corresponding proton energies were in the kinematically allowed region and where the contents

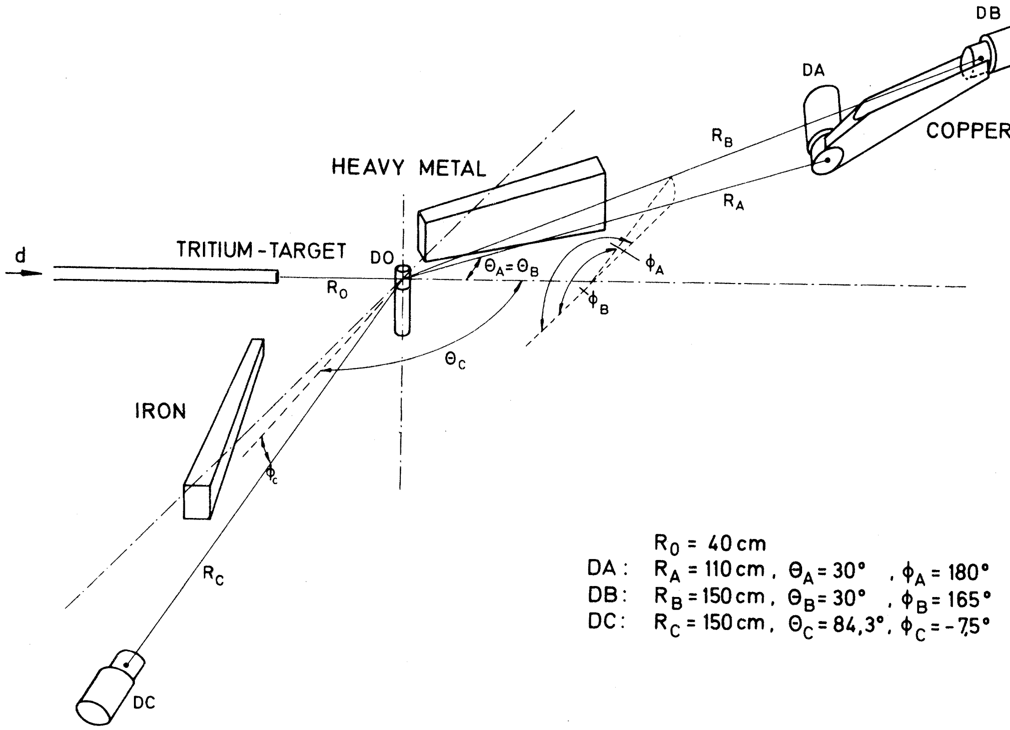

FIG. 1. Experimental arrangement. 18.4-MeV neutrons, produced by the reaction ^{3}H$(d,n)^4$He, bombard a scintillator of deuterated benzene, *DO*. The neutrons from deuteron breakup are detected in *DA* and *DB*, *DA* and *DC*, or *DB* and *DC*, respectively.

of the cell were more than one. The solid lines are the limits of the kinematically allowed region

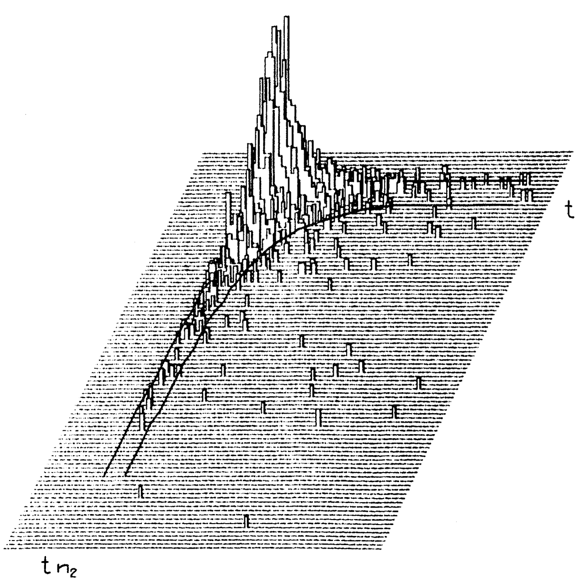

FIG. 2. Two-dimensional time-of-flight spectrum from the reaction ^{2}H$(n,2n)$H. t_{n1} is the neutron time of flight between the detectors *DO* and *DA*, t_{n2} that between *DO* and *DB*. All cells with more than one event are presented.

from a Monte Carlo simulation of the experiment.

In order to obtain a one-dimensional representation of the data, the measured events between these lines were projected on the curve for a point geometry. Figure 3(a) shows the resulting densities of events along the arc of this curve. Figure 3(b) gives the corresponding representation of the data with strong neutron-proton final-state interactions (*DO-DA-DC* coincidences).

To analyze the data, the calculated relative probability of each Monte Carlo event was multiplied with the reaction probability from the exact three-body theory[3] for the corresponding geometry and kinematics. Then for both cases the same projection procedure was carried out for the simulated data as described above for the measured data. This was done in the range of the $^1S_0$ neutron-neutron scattering length: $a_{nn} = -8.0$ fm to $a_{nn} = -24.0$ fm and the effective range between $r_{nn} = 1.0$ fm to $r_{nn} = 4.0$ fm. In all three-body calculations the triplet and singlet scattering parameters were kept fixed at the following values: $a_{np}{}^t = 5.42$ fm, $r_{np}{}^t = 1.75$ fm, $a_{np}{}^s = -23.68$ fm, and $r_{np}{}^s = 2.67$ fm. A simultaneous minimum χ^2 fit to the two experimental distributions with the same normalizing factor gave

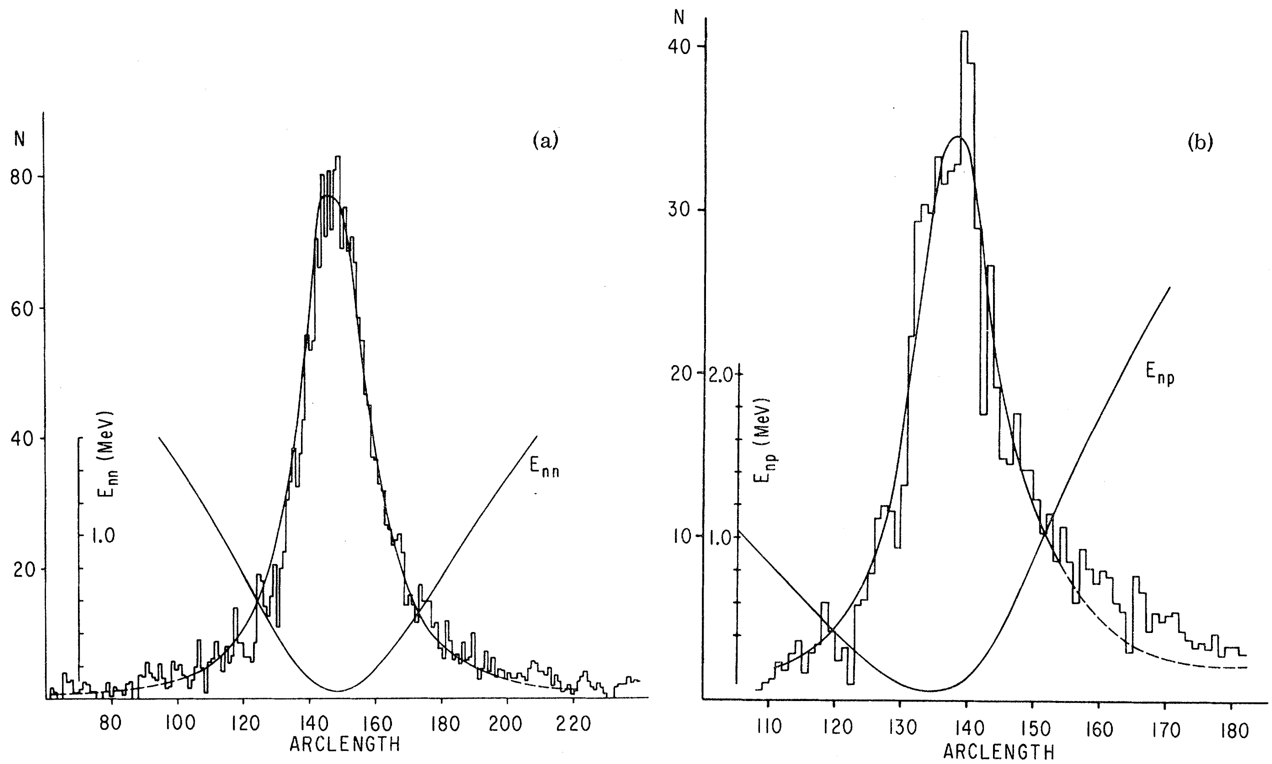

FIG. 3. Representation of (a) the *n-n* final-state interaction data and (b) the *n-p* final-state interaction data, projected on the kinematically allowed curves for a point geometry, versus the arc length along these curves. The upper solid lines show the theoretical distributions for $a_{nn} = -14.5$ fm and $r_{nn} = 2.7$ fm.

$a_{nn} = -14.5 \pm 0.8$ fm and $r_{nn} = 2.7 \pm 0.5$ fm. The resulting theoretical distributions are the upper solid curves in Figs. 3(a) and 3(b). The regions where the curves are dashed were not included in the analysis, mainly because of the uncertainty of the efficiencies of the neutron detectors for small neutron energy.

When the shape of the "neutron-neutron data" [Fig. 3(a)] was fitted alone it was found that this distribution was practically independent of r_{nn}. On the other hand the fit to the distribution of the "neutron-proton data" [Fig. 3(b)] alone showed sensitivity to r_{nn} but practically not to a_{nn}. The minimum χ^2 fit to the shape of the distribution of Fig. 3(a) alone gives $a_{nn} = -15.0 \pm 0.9$ fm.

The result of the analysis of the same data by Watson-Migdal approximation is $a_{nn} = -15.2 \pm 0.9$ fm. The difference to the value given earlier[4] ($a_{nn} = -16.0 \pm 1.0$ fm) is due to several improvements in the Monte Carlo simulation of the experiment and the inclusion of higher neutron-neutron relative energies in the analysis. The absolute value of the neutron-neutron scattering length obtained from our analysis by the three-body calculation is about 1.5 fm smaller than the weighted mean of the results from the experiments analyzed with a Watson-Migdal or Born approximation and the overlap of the mean statistical errors is poor.

Details of the application of the three-body calculation and a comparison with the results from other experiments will be published elsewhere.

[1]Recent compilations are E. Verondini, Riv. Nuovo Cimento 1, 33 (1971); W. T. H. van Oers, Particles and Nuclei 2, 207 (1971); J. S. C. McKee, in Proceedings of the Symposium on the Nuclear Three Body Problem, Budapest, 1971 (to be published); B. Zeitnitz, "$^1S_0$ Streuparameter aus Reaktionen mit drei Teilchen im Endzustand," Report of the II. Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany, 1972 (unpublished).

[2]R. T. Cahill and I. H. Sloan, Nucl. Phys. A165, 161 (1971).

[3]W. Ebenhöh, private communication, and to be published.

[4]Some results from the analysis using the Watson-Migdal approximation have been reported by R. Maschuw, P. Suhr, and B. Zeitnitz, in Proceedings of the Symposium on the Nuclear Three Body Problem, Budapest, 1971 (to be published).

[5]B. Zeitnitz, R. Maschuw, and P. Suhr, Nucl. Phys. A149, 449 (1970).