INFORMATION ABOUT THE NEUTRON-NEUTRON SCATTERING LENGTH FROM THE REACTION $H^3(n,d)2n$

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Recently the reactions $H^2(\pi^-,\gamma)2n$ and $H^2(n,p)2n$ were investigated with the aim of determining the neutron-neutron ${}^1S_0$ scattering length, a_{nn}. The preferred value for a_{nn} extracted from the first reaction is[1,2] −17 F, unfortunately with an uncertainty of about 5 F. Several investigations[3-5] of the second reaction gave values around −22 F. While the theoretical analysis of the reaction $H^2(\pi^-,\gamma)2n$ can be performed with an accuracy of ±1 F,[6] the reactions with more than two nucleons in the final state are considerably more difficult for interpretation.

In a reaction $a+A\rightarrow b+n+n$ the spectrum of the particle b reflects the neutron-neutron final-state interaction. However, distortive effects arise from at least two sources[7]:

(i) Interaction between b and the system $2n$. It is reasonable to expect that this depends upon the type of the particle b and on the relative b-$2n$ energy.

(ii) The interference between the n-n and the n-b resonances[8] and the interference between resonant and nonresonant processes.[9]

The study of the reaction $H^3(n,d)2n$ offers another possibility[4] to extract a_{nn}. The comparison of the reaction $H^2(n,p)2n$ and $H^3(n,d)2n$ allows one also to investigate the influence of the various distortive effects.

In order to determine kinematically such a reaction one has to measure five parameters. The measurement of the energy of the charged particle at 0° at a fixed incident energy is, thus, an incomplete measurement, and only that region of the spectrum which corresponds to the strong final-state interaction of the two neutrons is liable to meaningful interpretation.

The deuteron spectra from the reaction $H^3(n,d)2n$ at $E_n = 14.4$ MeV were measured with different detecting systems. The targets used were (1) a solid Cu-Ti-H^3 target containing 0.3 mg of H^3 and 10% of He^3; (2) two gas targets, one containing 0.1 mg and the other 1.3 mg of H^3, with the He^3 content less than 0.4%. The charged particles were detected with a semiconductor counter telescope[10] in conjunction with multidimensional analyzers.[11] The telescope consisted of two thin ΔE counters and an E counter depleted to detect 11.5-MeV protons. Two pulses (from the ΔE_2 and E counters) were analyzed by a 100×100-channel analyzer. The resulting three-dimensional graphs gave proton, deuteron, and triton ΔE_2-vs-E spectra simultaneously.[12] In a set of measurements three pulses (from the ΔE_1, ΔE_2, and E counters) were analyzed by a 100×100×100-channel analyzer. All those events for which ΔE_1 and ΔE_2 pulses did not satisfy specific criteria were rejected.[13]

The characteristics of the experimental setup were[14] discrimination between charged particles accurate to 1:500; energy resolution 600 keV; energy calibration accurate to 100 keV; measurement of the cross section for deuterons limited by background to $\gtrsim 0.1$ mb/sr. The absolute cross sections were determined by normalization to the elastic n-T[15] and n-D[16] cross sections. The rapid angular variation of these cross sections limited the accuracy of the absolute measurements to ±40%.

The deuteron spectrum at 0° obtained from the solid and 0.1-mg-H^3 gas target with the over-all He^3 contamination 8% is shown in Fig. 1(a), and the one from the 1.3-mg-H^3 gas target in Fig. 1(b). The peaks at 10.7 MeV originate from the reaction $He^3(n,d)H^2$. The groups at 8.8 MeV are due to the break-up $He^3(n,d)np$, and are related to the n-p final-state interaction. The pronounced peaks at 8 MeV are caused by the breakup $H^3(n,d)2n$ and correspond to the case when two neutrons are recoiling backwards in the c.m. system with nearly zero relative momentum. The n-d final-state interaction would kinematically correspond to 4.9-MeV deuteron energy. The absence of any enhancement around that energy is understandable since $d\sigma/dEd\Omega \sim a^2$, and $a_{nn} \gg a_{nd}$.

The cross section for the breakup $H^3(n,d)2n$ was calculated[17] in the Born approximation with a very crude model: The incident neutron picks up the proton to form a deuteron. The only perturbing interaction V_{np} was taken to be a square well. The final-state interaction of two neutrons was taken into account.

Figure 2 shows the 5.5- to 9-MeV data compared with the calculations performed for $a_{nn} = -17$ F, −22 F, and −27 F. The shape of the

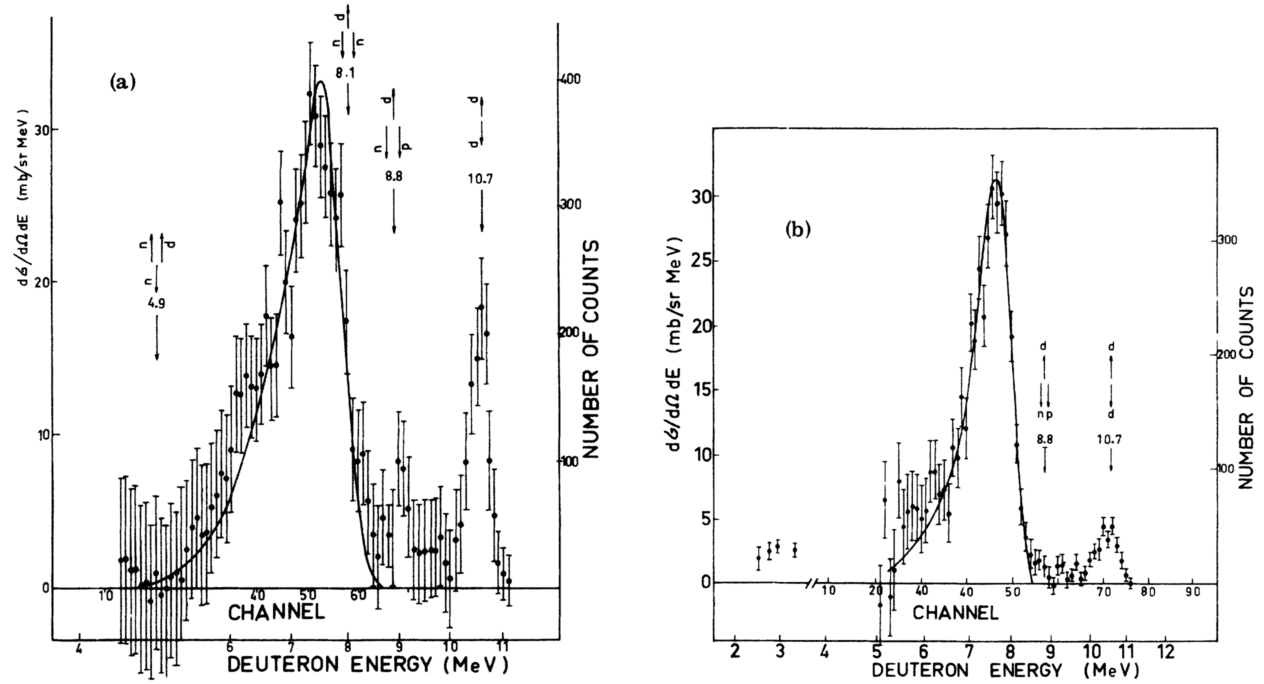

FIG. 1. The deuteron spectra at 0° from the reaction $n + H^3$ at $E_n = 14.4$ MeV. The arrows indicate the deuteron energies for the reactions $H^3(n,nd)n$, $H^3(n,d)2n$, $H^3(n,d)np$, and $He^2(n,d)H^2$. The solid curves are calculated in the Born approximation for the pickup process, and $a_{nn} = -17$ F. (a) Solid Cu-Ti-H^3 target and 0.1-mg-H^3 gas target; over-all He^3 content 8%; (b) 1.3-mg-H^3 gas target; He^3 content less than 0.4%.

spectrum indicates that the influence of distortive effects is small. This allows extension of the analysis to 6.3 MeV, about twice as far as was done for the reaction $H^2(n,p)2n$.[3] From the least-squares analysis one finds $a_{nn} = -18 \pm 3$ F.

It is constructive to compare the data and the results of this calculation with the Watson expression.[2] The difference between the Watson curve for $a_{nn} = -17$ F and the Born-approximation pickup curves is appreciable. This might serve as a measure for the region of validity of the Watson approach for this process.

The uncertainties in the theoretical approach prevent one from proceding with further analysis based on the extracted value of −18 F for a_{nn}. However, it is interesting to note that

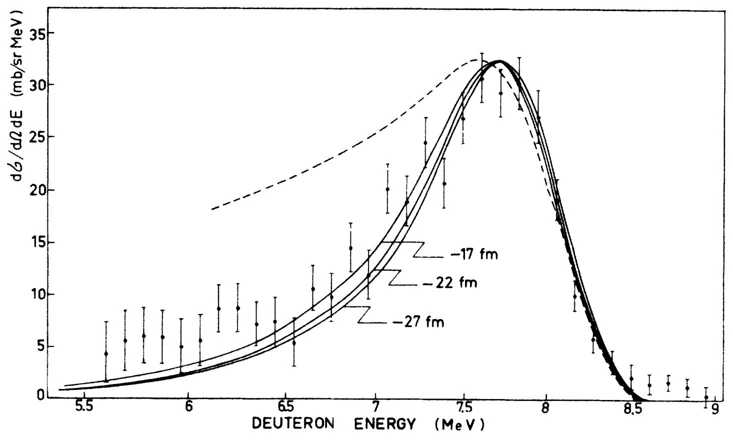

FIG. 2. The high-energy region of the deuteron spectrum from the reaction $H^3(n,d)2n$. The solid curves are calculated in the Born approximation for the pickup process with $a_{nn} = -17$ F, −22 F, and −27 F. The dashed curve is calculated with the Watson expression with $a_{nn} = -17$ F.

it departs from the value obtained from the reaction $H^2(n,p)2n$, and is closer to −17 F, the mean value obtained from the reaction $H^2(\pi^-, \gamma)2n$. The theoretical prediction for a_{nn}, assuming exact charge symmetry, lies between −16.6 and −16.9 F.[18]

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REACTIONS $H^3(n,p)3n$ AND $H^3(n,H^4)\gamma$ AT $E_n = 14.4$ MeV

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The proton spectra from the reaction $n + H^3$ at $E_n = 14.4$ MeV were measured with a semiconductor counter telescope[1] in conjunction with multidimensional analyzers.[2] The results of several independent measurements are summarized in Figs. 1 and 2. They reveal the following features:

(1) The cross section for the reaction $H^3(n, p)3n$, integrated from 3.8 to 5.1 MeV at 0°, is 12 mb/sr. This is smaller than the cross section for the breakup $H^3(n,d)2n$,[3] but is larger than predicted by Gammel and MacKellar.[4]

(2) The simultaneous breakup into three neutrons and a proton would give a proton energy spectrum of the form[5] $E_p^{1/2}(E_{\max}-E_p)^3$, with $E_{\max} = 5.1$ MeV. The failure to reproduce the experimental data can be interpreted as an indication of strong final interactions and gives hope[6] that the study of the reactions $H^3(n,p)3n$ and $He^3(p,n)3p$ might give some information about possible three-body forces.

(3) A group of protons extends from 5.9 to 6.9 MeV. Its width at half maximum is about 600 keV, comparable with the over-all resolution of the experimental arrangement. The total number of counts in this group is 892 ± 160.

The possible origin of this group was carefully examined. Separate measurements performed to this end showed that as much as 2% of hydrogen contamination of the targets could contribute no more than 0.3 mb/sr to this group. The reaction $N^{14}(n,p)C^{14}$ could give several groups of protons with energies above 7.5 MeV and one at 6.7 MeV. However, no protons with energies higher than 7 MeV, nor deuterons[3] from $N^{14}(n,d)C^{13}$, were observed. The possibility that the 6.4-MeV group stems from the N^{14} contamination was definitely ruled out by a separate measurement[7] of the reaction $n + N^{14}$. Since the intensity of the 6.4-MeV proton group was independent of the amount of He^3 in the target, as is evident from Figs. 1 and 2, it could not be assigned to the $n + He^3$ interaction. Several measurements performed in different experimental conditions have excluded also the possibility that this group is due to an experimental error.

The remaining alternative is to assign the 6.4-MeV proton group to the $n + H^3$ interaction. If one accepts this, one is obliged to assume the existence of a bound state of three neutrons. Its binding energy would then be about 1 MeV and the cross section $\sigma(\varphi = 0°)_{H^3(n,p)n^3} = 3.8$ mb/sr.