DETERMINATION OF THE NEUTRON-NEUTRON SCATTERING LENGTH FROM THE REACTION T(d, He^3)2n†

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Recent papers[1] have re-emphasized the need for an accurate determination of the neutron-neutron $^1S_0$ scattering length a_n, since comparison with the pp and np scattering lengths, a_p and $^1a_{np}$, provides a test of charge symmetry and charge independence in the nucleon-nucleon interaction.

Several determinations of a_n have recently been reported.[2-5] The reactions studied experimentally fall into two categories: (1) the reaction $\pi^- + d \rightarrow 2n + \gamma$, with only two strongly interacting particles in the final state, and (2) the reactions D(n,p)2n and T(n,d)2n which have three particles that may interact strongly in the final state. The most recent investigation[4] of the $\pi^- + d$ reaction has resulted in the preliminary value

$$a_n = -16.4 \pm 1.3 \text{ F},$$

where the sign was assumed and the error introduced by the theoretical uncertainties[6] was not included in the quoted probable error. In contrast, analyses of the data from the reaction D(n,p)2n at 14 MeV have given the values[2,3]

$$a_n = -21 \pm 2 \text{ F}$$

and

$$a_n = -23.6^{+2.0}_{-1.6} \text{ F},$$

which are consistent within themselves but which do not agree with the $\pi^- + d$ result. Finally, the reaction T(n,d)2n has provided the value[5]

$$a_n = -18 \pm 3 \text{ F}.$$

Neither the D(n,p)2n nor the T(n,d)2n spectra could be interpreted in terms of the final-state neutron-neutron interaction alone.[7-9] Therefore, treatments were used that included interactions with the third final-state particle[3] or effects produced by the reaction mechanism itself.[5] The discrepancies among the values obtained for a_n clearly indicate the need for a test of the theory used to determine a_n from experiments other than that of neutron-neutron scattering.

We report here a determination of a_n from analysis of He^3 spectra from the reaction T(d, He^3)2n. Also, triton spectra were obtained from the mirror reaction He^3(d,t)2p. Analysis of these spectra for a determination of a_p, which is well established[10] ($a_p = -7.719 \pm 0.008$ F) from low-energy proton-proton scattering data, provides a direct test of the theory used to deduce a_n.

The reaction He^3(d,t)2p has been investigated by several groups,[11-16] and it has been shown that there is a good semiquantitative agreement between the final-state-interaction calculations and the measured triton spectra.[12,15] The reaction T(d, He^3)2n was first studied several years ago.[17]

The present experiment was carried out at the Berkeley 88-inch variable-energy cyclotron. The reaction T(d, He^3)2n was studied at deuteron energies (E_d) of 32.5 and 40.2 MeV. The He^3 spectra were obtained with a resolution of 240 keV at several laboratory angles between 6° and 25°. The He^3(d,t)2p was studied at $E_d = 29.8$ MeV (to match the final-state c.m. energy of the previous reaction at 32.5 MeV) with a resolution of 140 keV. The experimental techniques were essentially the same as described in an earlier paper.[12]

Figure 1(a) contains the triton spectrum measured at a laboratory angle of 8°, and Fig. 1(b) exhibits the He^3 spectrum taken at 6°. The fitted curves were calculated from the Watson-Migdal theory. At these angles, no effects of p-T or n-He^3 final-state interactions were seen. It has been established that both reactions proceed through a direct reaction mechanism at small angles,[11,13,14,17] consistent with an $l = 0$ nucleon transfer. The peripheral nature of the reaction then implies a small overlap of the outgoing T or He^3 wave function with the wave function of the nucleon pair, and thus a suitable description should be provided by a dominant nucleon-nucleon final-state interaction.

In the studied rearrangement collisions the

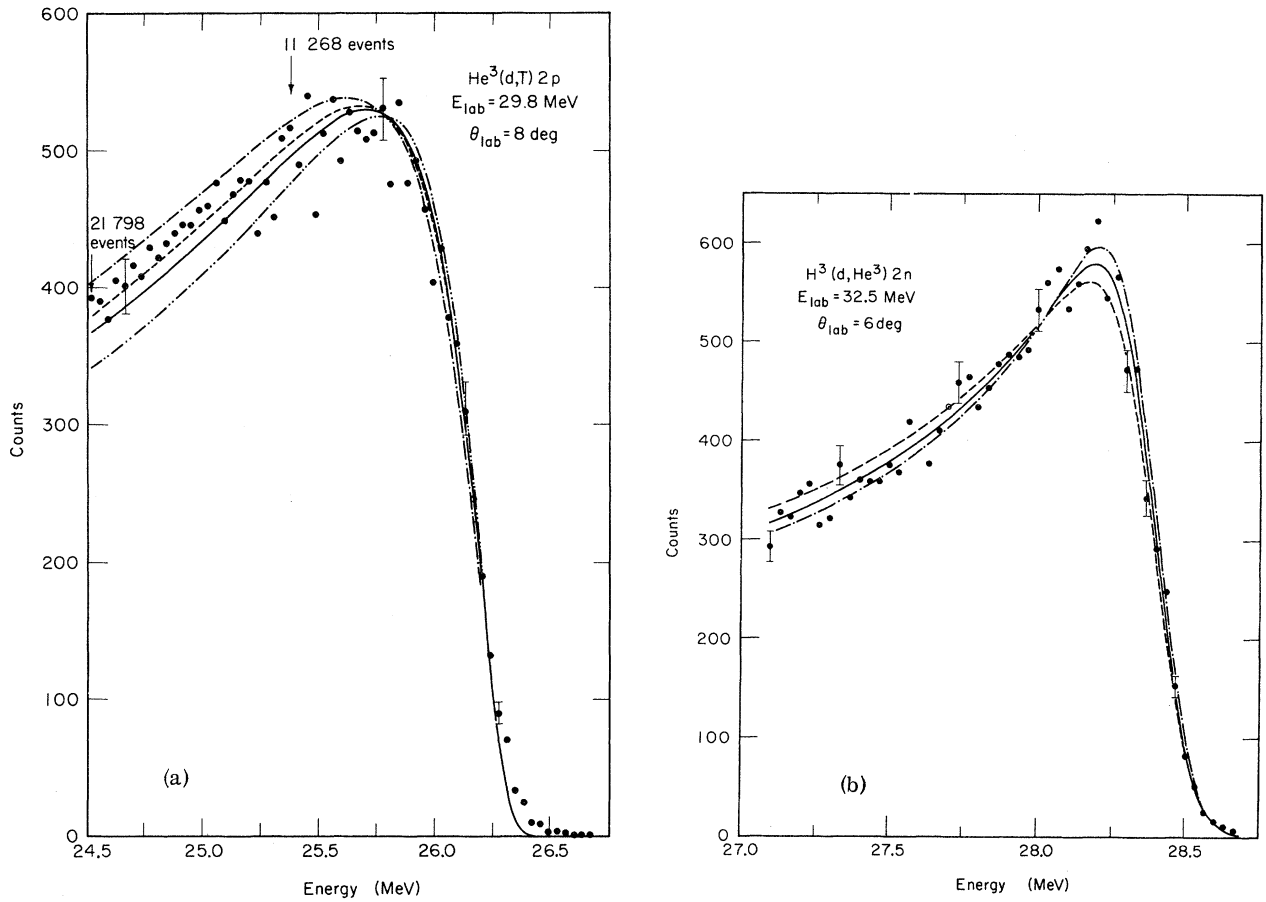

FIG. 1. (a) Triton spectrum at 8° lab of the reaction $He^3(d,t)2p$ at 29.8 MeV with theoretical fits calculated for 11 268 events and for 21 798 events. The dots are experimental points. The solid line is the best fit for 11 268 events with $a_p = -7.69$ F. The dashed line is the best fit for 21 798 events with $a_p = -7.41$ F. The dash-dot line is obtained with $a_p = -6.90$ F, for 11 268 events, and the dash-double dot line is obtained with $a_p = -8.33$ F; they indicate the sensitivity of the theoretical curve to variation of a_p. (b) He^3 spectrum at 6° lab of the reaction $T(d, He^3)2n$ at 32.5 MeV with theoretical fits calculated for 17 782 events. The solid line is the best fit for $a_n = -16.1$ F. The dashed line is obtained with $a_n = -14.0$ F and the dash-dot line corresponds to $a_n = -18.0$ F.

differential cross section can be expressed as

$$\frac{d^2\sigma}{dE\,d\Omega} = \frac{2\pi}{\hbar}\frac{1}{v_d}|T_{if}|^2\rho(E), \tag{1}$$

where T_{if} is the transition matrix element and $\rho(E)$ is the phase-space factor. The general form of T_{if} is $T_{if} = \int\psi_f^\dagger V_I \psi_i d\tau$, where V_I is the interaction causing the rearrangement. For the reaction $T(d, He^3)2n$ at small angles, we can write[7] $\psi_f = \Psi_{He^3}\varphi_R f(r)(e^{i\delta}\sin\delta)/k$, and therefore

$$T_{if} = \frac{e^{-i\delta}\sin\delta}{k}\int[f(r)\Psi_{He^3}\varphi_R]^\dagger V_I \psi_i d\tau = g(\theta)\frac{e^{-i\delta}\sin\delta}{k}. \tag{2}$$

The term $(e^{-i\delta}\sin\delta)/k$ comes in simply through the S wave function of the neutron pair in the final state, δ is the singlet S-wave phase shift, $\hbar k$ is the relative nucleon-nucleon momentum, Ψ_{He^3} is the internal wave function of He^3, and φ_R describes the relative motion between the He^3 nucleus and the neutron pair. The function $g(\theta)$ depends on the reaction mechanism, θ being the c.m. angle of the ob-

served particle (i.e., He^3).

For the reaction $T(d,He^3)2n$, we have used

$$|T_{if}|^2 = |g(\theta)|^2 \frac{1}{E_{2n} + (\hbar^2/m_n)(-1/a_n + \gamma_n E_{2n})^2}, \quad (3)$$

and for the reaction[8] $He^3(d,t)2p$,

$$|T_{if}|^2 = |g(\theta)|^2 \frac{C(\eta)}{C^2(\eta)E_{2p} + (\hbar^2/m_p)[-1/a_p - h(\eta)/R + \gamma_p E_{2p}]^2}, \quad (4)$$

where $C(\eta) = 2\pi\eta/(e^{2\pi\eta}-1)$, a_p is the scattering length, $\eta = e^2/\hbar v$, $h(\eta) = \mathrm{Re}[\Gamma'(-i\eta)/\Gamma(-i\eta)] - \ln\eta$, $R = \hbar^2/m_p e^2$, $\gamma_n = 3.19\times10^{11}$ MeV^{-1} cm^{-1}, corresponding to an effective range $r_e = 2.65$ F, $\gamma_p = 3.40\times10^{11}$ MeV^{-1} cm^{-1}, and E_{2n} (E_{2p}) is the relative nucleon-nucleon energy. In both cases $\rho(E) = CE^{1/2}(E_{\max}-E)^{1/2}$, where E is the c.m. energy of the observed particle with a maximum value $E_{\max}$.

Using expressions (3) and (4) converted to the laboratory system with the Jacobian transformation, we have obtained fits for the spectra of both reactions. Experimental values for $|g(\theta)|^2$ were used and the instrumental resolution was folded in. The section of the spectrum of the reaction $He^3(d,t)2p$ shown in Fig. 1(a) contains 21 798 events. It is roughly equivalent to the section of the $T(d,He^3)2n$ spectrum shown in Fig. 1(b) ($E_{2n} = 0$ to 1.57 MeV) which was used to extract a_n. From the reaction $He^3(d,t)2p$, we obtained, for 11 268 events, the value

$$a_p = -7.69^{+0.61}_{-0.67}\ \mathrm{F},$$

and for 21 798 events

$$a_p = -7.41^{+0.39}_{-0.49}\ \mathrm{F},$$

using a minimum-χ^2 criterion. The errors are the probable errors determined from a normal χ^2 distribution. Calculations were also done with changes of all experimental input parameters, such as $|g(\theta)|^2$, E_d, and the energy resolution, within their respective limits of error, and no significant changes resulted for the scattering length. The 0.3-F difference between the value for 21 798 events and the value obtained from proton-proton scattering is still within our probable error.

For the reaction $T(d,He^3)2n$ at $E_d = 32.5$ MeV, the best fit for 17 782 events yields

$$a_n = -16.1 \pm 1.0\ \mathrm{F}.$$

Also, the value of a_n is stable to within 0.2 F irrespective of the section of the spectrum (up to $E_{2n} = 1.57$ MeV) employed for the fit. Even though we estimate from the comparison between our a_p result and its established value that 0.6 F is the upper limit of error due to theoretical uncertainties, we consider this stability of a_n to be a good indication that this error is in fact smaller. A fit with a positive scattering length yielded $a_n = 18.4 \pm 1.1$ F.

Since our spectra were fitted over an energy range from zero to 1.57 MeV in the neutron-neutron c.m. energy, we were able to obtain a χ^2 fit for the effective-range parameter r_e. The value used in the fits for a_n was $r_e = 2.65$ F; then, for the best value $a_n = -16.1$ F, variation of r_e gave a best fit for $r_e = 3.2 \pm 1.6$ F.

We have made a determination of the sign of a_n, assuming that in both reactions $|g(\theta)|^2$ in expressions (3) and (4) are the same to within a few percent. Then the reaction $He^3(d,t)2p$ can be used to determine $|g(\theta)|^2$ which in turn can be used to predict the $T(d,He^3)2n$ absolute yield for both signs of a_n. Fig. 2(a) contains the pertinent plots, and it is seen that the comparison with the experimental spectrum is consistent with the negative sign. The spectrum calculated with the positive scattering length does not include the contribution[3,8] from the resulting bound state. This contribution would increase the discrepancy between the calculated and experimental spectra. In fact, a bound-state contribution given by $(d\sigma/d\Omega)_{\mathrm{bound}} \simeq 0.4\int(d^2\sigma/d\Omega dE)dE$ would make it impossible to fit the shape of the measured spectrum. This independent evidence for negative a_n would provide support for the assumption of

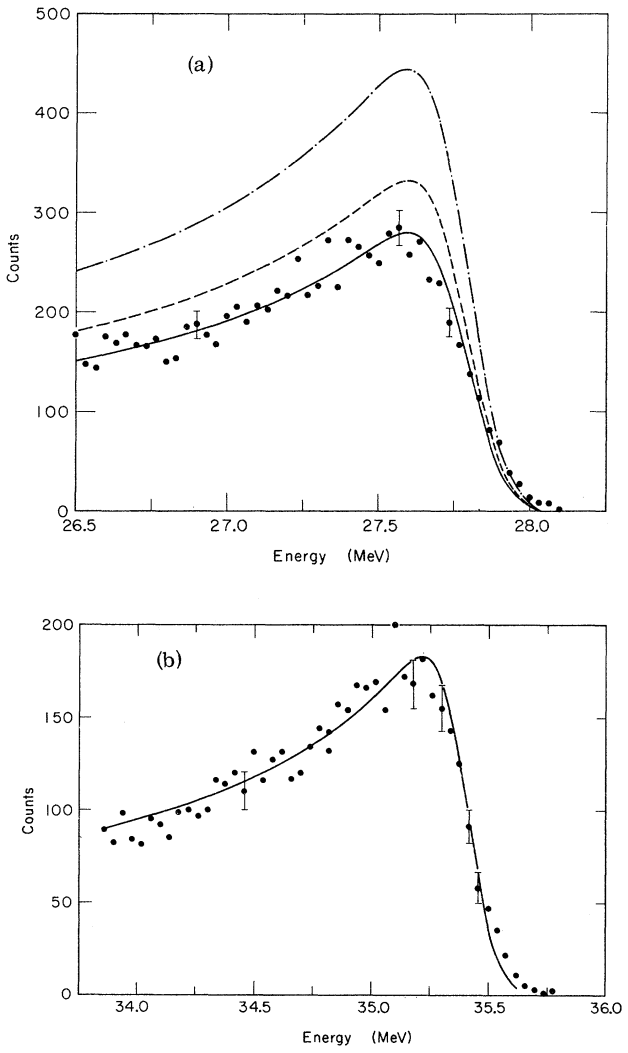

FIG. 2. (a) He^3 spectrum at 8° lab of the reaction $T(d,He^3)2n$ at 32.5 MeV together with the theoretical fit for $a_n = -16.0$ F, shown with solid line. The fit is consistent with the value determined for the 6° spectrum. The dashed line is a prediction for $a_n = -16.0$ F using the $|g(\theta)|^2$ determined from the reaction $He^3(d,t)2p$, and the dash-dot line for $a_n = +18.4$ F. (b) He^3 spectrum at 8° lab of the reaction $T(d,He^3)2n$ at 40.2 MeV together with the curve calculated for $a_n = -16.0$ F. It is consistent with the value determined at 32.5 MeV.

near equivalence of $|g(\theta)|^2$ for the mirror reactions.

Our determination of

$$a_n = -16.1 \pm 1.0 \text{ F}$$

compares well with the $\pi^- + d$ result and with the value −16.4 to −16.9 F predicted by Heller, Signell, and Yoder[1] from a_p on the basis of a charge-symmetric nucleon-nucleon interaction.

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