Precise Determination of Triton D-State Parameters Using Transfer Reactions at Sub-Coulomb Energies

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Angular distributions of cross sections and tensor analyzing powers have been measured for ground state transitions in ^{95}Mo$(d,t)^{94}$Mo, ^{119}Sn$(d,t)^{118}$Sn, and ^{149}Sm$(d,t)^{148}$Sm for deuteron energies below the Coulomb barrier. Exact, finite-range distorted-wave Born approximation analyses of these data have been made using both the S- and D-state amplitudes for the three-nucleon systems. A best fit of the data gives $D_2(t) = -0.217 \pm 0.010$ fm^2 and $\eta_t = -0.043 \pm 0.002$, significantly lower than previous experimental determinations, and in agreement with a recent theoretical prediction of $\eta_t = -0.046 \pm 0.001$.

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In order to distinguish between different trinucleon bound state wave functions generated from various "realistic" models of the nucleon-nucleon (NN) interactions, the asymptotic D-to-S-state ratio η and the D_2 parameter [1] are now considered important observables. These quantities have an especially strong dependence on tensor forces believed to originate mainly from an internucleon one-pion-exchange interaction [1]. Beyond providing a sensitive test of theoretical calculations, these measures of the trinucleon D state allow better determination of the polarization of neutrons or protons in polarized targets of ^{3}He or tritium [2]. Polarized ^{3}He targets are currently under study for use as polarized neutron targets at hadron and electronuclear facilities.

Reliable theoretical predictions of η and D_2 for ^{3}H [η_t and $D_2(t)$, respectively] have improved dramatically over the last decade [3-6]. The calculations are now highly sophisticated, based on realistic Hamiltonians including three-nucleon interactions, and give binding energies of the trinucleon systems to within 10 keV of the measured values [7]. These calculations also indicate a smooth dependence of η_t and rms radius on the predicted triton binding energy [6]. Using the Reid soft core [8] and Argonne V14 (Ref. [9]) two-body forces plus the two-pion-exchange three-nucleon-force models of the Tucson-Melbourne (TM) [10] and Brazilian [11] groups, Friar *et al.* [6] performed calculations of the trinucleon S- and D-wave asymptotic normalization constants. Interpolating the observables as a function of binding energy they extracted a value of $\eta_t = -0.046 \pm 0.001$. Ishikawa and Sasakawa [3,4] performed a similar calculation using four different two-nucleon potentials and the TM three-nucleon potential. Incorporating their calculations for different values of the cutoff mass of the πNN monopole form factor they predict a value of $\eta_t = -0.0432 \pm 0.0015$. A synopsis of these recent theoretical calculations is tabulated in Table III of Ref. [6].

To substantiate these theoretical predictions, and achieve the goal of discriminating different trinucleon wave functions through these physical observables such as D_2 and η_t, experimental determinations of these observables with sufficient accuracy and precision are needed [6]. One determination has come from the extrapolation of tensor analyzing powers (TAP) to the nucleon transfer pole (ETAP) [12]. A value of $\eta_t = -0.050 \pm 0.006$ was reported [12] using this technique, but the uncertainty in this result is far too large to be useful in distinguishing between predictions of various theoretical models. Moreover, the technique of determining the errors by ETAP has been questioned by Londergan, Price, and Stephenson [13]. They claimed that the procedure excludes truncation errors and that actual errors may be larger than originally estimated. Determinations based on analyses of TAP for (d,t) reactions have also been reported [14-16]. Sen and Knutson [14] have performed distorted-wave Born approximation (DWBA) calculations for sub-Coulomb (d,t) reactions with a local-energy approximation and obtained $D_2 = -0.288 \pm 0.011$ and -0.259 ± 0.014 fm^2, somewhat larger in magnitude than most theoretical predictions [4]. Other studies [15,16] employed more realistic exact finite-range DWBA calculations of (d,t) reactions and estimated $\approx 20\%$ uncertainty in the extracted D_2 values. The purpose of this paper is to report a new, more accurate determination of the D-state parameters by analyzing high-precision TAP measurements obtained in sub-Coulomb (d,t) reactions using exact finite-range DWBA calculations. TAP calculated for this reaction at sub-Coulomb energies are approximately zero when no triton D state is included and scale directly with the triton D-state amplitude. Hence comparisons of calculations with measured TAP values at sub-Coulomb energies can provide an extremely sensitive determination of the D-state parameters D_2 and η_t.

These DWBA analyses of (d,t) reactions assume an inert deuteron picking up a neutron as it passes the nucleus to form a triton. The reliability of DWBA theory is improved by measurements of reactions with low Q values at sub-Coulomb energies so that the interaction region is localized well outside the nuclear surface. Moreover, since Coulomb forces predominate, the calculated

TABLE I. Sub-Coulomb (d,t) reactions investigated with Q value and angular momentum transfer.

Target	E_d (MeV)	j^π	Q value (MeV)	% below E_C[a]
^{95}Mo	7	$\frac{5}{2}^+$	−1.11	13
^{119}Sn	6,7	$\frac{1}{2}^+$	−0.23	33,22
^{149}Sm	8	$\frac{7}{2}^-$	0.38	24

[a] E_C represents the Coulomb barrier for deuterons calculated as $E_C = Z_t \times 1.44/[r_C(A_t^{1/3}+2^{1/3})]$ MeV.

TAP are insensitive to the choice of nuclear optical model potential (OMP) parameters.

Using the new high-intensity polarized source at Triangle Universities Nuclear Laboratory [17], measurements have been made of differential cross section $[\sigma(\theta)]$ and two TAP (A_{yy} and A_{zz}) in the angular range of $85° \le \theta_{lab} \le 165°$ for ^{95}Mo$(d,t)^{94}$Mo at 7 MeV, ^{119}Sn$(d,t)^{118}$Sn at 6 MeV, and ^{149}Sm$(d,t)^{148}$Sm at 8 MeV. In addition, the $\sigma(\theta)$ and A_{zz} have been measured for ^{119}Sn$(d,t)^{118}$Sn at 7 MeV. The reactions with their Q values and j^π transfer are tabulated in Table I. The reactions chosen for the present work have j transfer given by $j = l + \frac{1}{2}$, to provide a maximal effect of the D-state amplitude on the TAP [18]. The reactions considered have unique l transfer so that one can avoid the ambiguity of incoherent sums of spectroscopic amplitudes.

The DWBA calculations for $\sigma(\theta)$ and TAP were carried out using the computer code PTOLEMY [19]. Global OMPs for the deuteron [20] and triton [21] channels were used in the calculations. A complex tensor potential [22] was also used in the deuteron channel and produced an effect of $\approx 2\%$ in the predicted TAP for these sub-Coulomb transitions. For each transition studied, the value of η_t was separately adjusted to obtain the minimum χ^2 per degree of freedom (χ^2/N). Figures 1 and 2 show the best fit of TAP data for each transition obtained by varying η_t. Best-fit η_t values and the corresponding χ^2/N are tabulated in Table II. In all transitions, values of χ^2/N are near 1, indicating that theoretical calculations reproduce experimental measurements very well. The uncertainty given for η_t in Table II reflects the statistical uncertainty and systematic and statistical error in the beam polarization determination only. Using these values we obtained a statistically weighted average of $\eta_t = -0.043 \pm 0.001$. The statistically weighted average obtained for D_2 using a comparable technique is -0.217 ± 0.010 fm^2. Other systematic errors are discussed below.

Several tests were made to check the sensitivity of the extracted η_t to various choices of input into the DWBA calculations. It was observed that a change in deuteron or triton OMP parameters [23] only affected the differential cross sections, while TAP values changed by less than 1%. A maximum variation for η_t of about ± 0.0002 was obtained based on the choice of reasonable OMP parameters. The wave function of the neutron in

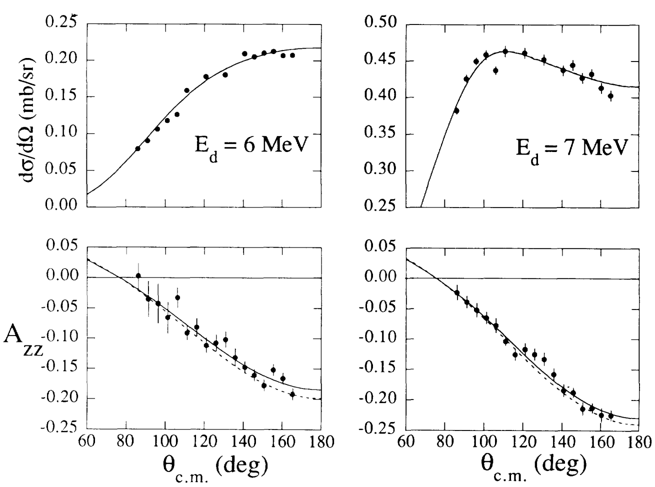

FIG. 1. Angular distributions of $d\sigma/d\Omega$ (arbitrarily normalized) and $A_{zz}(\theta)$ for the ground state transition of ^{119}Sn$(d,t)^{118}$Sn at $E_d = 6$ and 7 MeV. The solid curve results from an exact, finite-range DWBA analysis using best-fit η_t given in Table II, while the dashed curve results from $\eta_t = -0.046$.

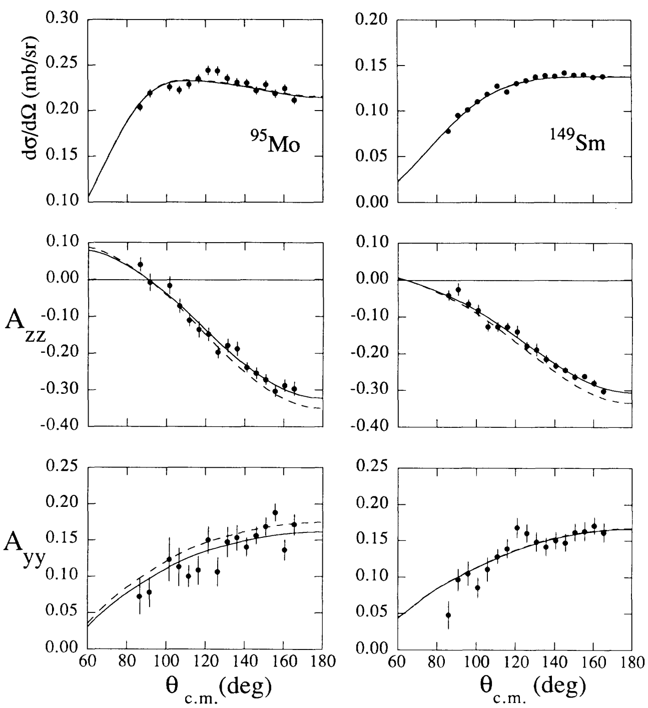

FIG. 2. Angular distributions of $d\sigma/d\Omega$ (arbitrarily normalized), $A_{zz}(\theta)$, and $A_{yy}(\theta)$ for the ground state transition of ^{95}Mo$(d,t)^{94}$Mo at $E_d = 7$ MeV and ^{149}Sm$(d,t)^{148}$Sm at $E_d = 8$ MeV. The solid curve results from an exact, finite-range DWBA analysis using best-fit η_t given in Table II while the dashed curve results from $\eta_t = -0.046$.

TABLE II. Best-fit η_t values obtained for different (d,t) reactions.

Target	E_d (MeV)	TAP	$10^2\eta_t$	χ^2/N
^{95}Mo	7	A_{zz}	-4.17 ± 0.39	0.85
		A_{yy}	-4.19 ± 0.52	1.40
^{119}Sn	6	A_{zz}	-4.24 ± 0.39	1.23
		A_{yy}	-4.92 ± 0.71	1.11
	7	A_{zz}	-4.36 ± 0.32	0.94
^{149}Sm	8	A_{zz}	-4.17 ± 0.21	0.90
		A_{yy}	-4.58 ± 0.42	1.12

the target nucleus was generated using the separation-energy method, where the neutron is assumed to be bound in a Woods-Saxon (WS) well. For a given value of well radius and diffuseness the potential depth was adjusted to give the correct binding energy of the neutron with the residual nucleus. The sensitivity of η_t to the choice of well geometry was tested by varying the radius of this well. The TAP predictions were insensitive to these parameters although the overall magnitude of the predicted $\sigma(\theta)$ varied somewhat. The radial form factors at the projectile vertex for the lighter system (which in this case is the deuteron with the neutron) were calculated using the same separation-energy method. The variation of η_t caused by 20% variations of WS geometrical parameters was investigated and no effect was observed in predicted TAP. A well geometry of $r=1.5$ fm and $a=0.5$ fm was used in the final calculations of the triton bound state wave function [16].

In our DWBA calculations we assumed that the wave functions of the deuteron and triton are free particle wave functions. The effect of the Coulomb field of the target, however, can give rise to virtual excitations and, as such, can induce nonspherical components into the deuteron and triton wave functions. A study of these effects on TAP for sub-Coulomb (d,p) reactions was made by Tostevin and Johnson [24] who found that the effect on the deuteron contributes $\approx 3\%$ to the TAP magnitudes. One might expect smaller effects in (d,t) reactions since the triton wave function alone strongly influences the TAP [25] and tritons are less sensitive to Coulomb distortions than deuterons because of their larger binding energy. Deuteron D-state contributions are also expected to be insignificant because of the lack of sensitivity of the TAP in (d,t) reactions to the deuteron wave function [26].

No attempt was made to evaluate effects of other possible reaction mechanisms such as inelastic target excitation following neutron transfer. The present measurements were performed at sub-Coulomb energies where multistep processes are expected to be unimportant since the coupling between various reaction channels is very weak [25]. In the absence of reliable theoretical calculations of these effects we assume their contribution to the total error to be $\pm4\%$, i.e., ±0.0017. Clearly more theoretical work is needed to validate this error estimate. Combining this with the statistical and fitting error of ±0.0012 gives a final error in η_t of ±0.002.

In summary, we have obtained highly accurate angular distributions of $\sigma(\theta)$, A_{zz}, and A_{yy} for three (d,t) reactions at incident deuteron energies below the Coulomb barrier. Our goal has been to determine η_t with an accuracy sufficient to be of use in distinguishing between various realistic NN interactions [6]. In order to make this determination, exact finite-range DWBA calculations were compared to data obtained at sub-Coulomb energies for transitions of different j^π which were chosen to have maximal D-state effects. Our results appear independent of Z of the target, angular momentum transfer, and incident energy provided it remains sufficiently far below the Coulomb barrier. The results of the analysis are independent of the geometry of the bound state wave function and choice of the OMP parameters. The present high-precision result, $\eta_t=-0.043\pm0.002$, agrees well with the theoretical prediction [6] of $\eta_t=-0.046\pm0.001$ and disagrees with a weighted average of previous experimental determinations [12] ($\eta_t=-0.054\pm0.0013$). In addition, it is closer to the average of experimental determinations made of η for ^{3}He ($\eta_{^3\mathrm{He}}=-0.037\pm0.003$) [12]. Using our η_t value, a ratio of $\eta_t/\eta_{^3\mathrm{He}}=1.16\pm0.11$ is obtained, in agreement with a theoretical prediction of 1.07 given in Ref. [6].

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