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Determination of the D_2 parameter for (d,t) reactions

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Measurements of the tensor analyzing powers have been obtained for $(\vec{d},t)$ reactions on ^{91}Zr, ^{118}Sn, ^{119}Sn, and ^{208}Pb for deuteron energies both above and below the Coulomb barrier. The measurements are sensitive to the presence of D-state components in the triton wave function and allow the determination of a parameter D_2. This parameter is a measure of the importance of triton wave function components in which one neutron moves with orbital angular momentum $L = 2$ relative to the deuteron center of mass. Values of D_2 are extracted from the tensor analyzing power measurements by making use of distorted-wave Born approximation calculations. Analysis of the sub-Coulomb measurements leads to $D_2 = -0.279 \pm 0.012$ fm^2, which is somewhat larger in magnitude than recent theoretical predictions.

[NUCLEAR REACTIONS ^{91}Zr(d,t), E_d=6.0, 7.5 MeV, ^{118}Sn(d,t), E_d=12.0 MeV, ^{119}Sn(d,t), E_d=6.0, 7.5, 9.0 MeV, ^{208}Pb(d,t), E_d=10.0, 12.3 MeV; measured polarization parameters $T_{20}(\theta)$, $T_{21}(\theta)$, $T_{22}(\theta)$; deduced D_2. Enriched targets, DWBA analysis.]

I. INTRODUCTION

It has long been recognized that the three-nucleon problem plays a central role in nuclear physics. Although the study of any light nucleus is interesting in its own right, the three nucleon system is of special importance, because in this case, it is possible to carry out quantum mechanical calculations which are essentially exact. This in turn allows one to investigate the question of whether nucleon-nucleon interactions determined from two-body experiments are able to explain the properties of complex nuclei. Unfortunately, experiments have not provided us with a great deal of useful information about the properties of the ^{3}H and ^{3}He wave functions. For the most part, comparisons between three-nucleon bound-state calculations and experiment are limited to the binding energy and the charge form factor.

It has been demonstrated[1] that one can obtain experimental information about the D-state components of the triton wave function by measuring the tensor analyzing powers for $(\vec{d},t)$ reactions. In particular, the measurements allow one to determine the value of a single parameter, D_2. In general, (d,t) reactions are sensitive to those components of the triton wave function which look like a neutron coupled to a deuteron, and the parameter D_2 is a measure of the importance of the component in which the neutron moves with orbital angular momentum $L = 2$ relative to the deuteron center of mass.

Measurements of the tensor analyzing powers have previously been reported for a number of $(\vec{d},t)$ reactions.[2-5] The values of D_2 extracted from these data range from -0.24 to -0.30 fm^2. The empirical D_2 results agree quite well with the theoretical value, -0.24 fm^2, which has been obtained[6] from a Faddeev calculation of the triton wave function.

In this paper we present the results of a series of $(\vec{d},t)$ experiments. Measurements of the three tensor analyzing powers (T_{20}, T_{21}, and T_{22}) have been obtained for ^{91}Zr$(\vec{d},t)^{90}$Zr at 6.0 and 7.5 MeV, for ^{118}Sn$(\vec{d},t)^{117}$Sn at 12.0 MeV, for ^{119}Sn$(\vec{d},t)^{118}$Sn at 6.0, 7.5, and 9.0 MeV, and for ^{208}Pb$(\vec{d},t)^{207}$Pb at 10.0 and 12.3 MeV. The measurements will be analyzed to obtain new empirical D_2 values.

In Sec. II we present some background information, including a rigorous definition of D_2 and a discussion of the advantages which result from the use of sub-Coulomb energies. The experimental details are given in Sec. III, and the analysis of the measurements is presented in Sec. IV. In Sec. V the results are discussed and a comparison between the experimental and theoretical D_2 values is presented. Some of the measurements described in this paper have previously been reported elsewhere.[1,3]

II. BACKGROUND

It is well known that (d,t) reactions on medium- and heavy-weight nuclei can usually be understood in terms of the standard distorted-wave Born approximation (DWBA), in which one assumes that the reaction occurs through a simple one-step process. In this approximation the deuteron is treated as an inert particle which, as it passes the target nucleus, picks up a neutron to form the trition. It is easily seen that two distinct angular momentum coupling schemes are allowed in the $n + d \to t$ process. The first possibility is an S state in which the $n-d$ relative orbital angular momentum L is zero and the total spin, defined as the vector sum of the neutron and deuteron spins, is $\frac{1}{2}$. Second, the neutron and deuteron may combine in a D-state configuration in which the orbital angular momentum, $L=2$, and the total spin, which is $\frac{3}{2}$ in this case, couple to give a $j^{\pi}=\frac{1}{2}^{+}$ final state.

The relative importance of $L=0$ and $L=2$ transfers in a (d,t) reaction will, of course, depend on the extent to which the corresponding configurations are present in the triton wave function. Since the triton consists primarily of three nucleons in a relative S state, the $L=0$ configuration will be dominant; however, reactions with $L=2$ also occur, since the triton wave function contains D-state components which have the appropriate configuration. It can be shown[1] that the tensor analyzing powers for a (d,t) reaction are sensitive to the presence of $L=2$ contributions, and thus measurements of these quantities can provide

information about the D-state components of the

Since DWBA is used to determine D_2 from the measurements, the reliability of this approximate reaction theory is an important issue. In general, DWBA calculations reproduce the main qualitative features of cross section and analyzing power measurements, but are not accurate in a quantitative sense. Thus, it seems unlikely that tensor analyzing power measurements for arbitrarily chosen (d,t) transitions would lead to an accurate determination of D_2. However, it is known[9] that the reliability of DWBA calculations improves significantly for (d,t) reactions carried out below the Coulomb barrier. The calculations are expected to be particularly accurate for transitions which have Q values close to zero. Under these conditions the (d,t) reactions occur well outside the nuclear surface. This results in part from the use of sub-Coulomb energies, which prevents the deuteron and triton from penetrating into the nuclear interior. The importance of the $Q\approx 0$

condition is that it leads to a situation in which the lyzing powers result from the D-state component of the deuteron wave function. The value of D_2 for (d,p) reactions is fairly well known from other work (D_2 depends on the long-range parts of the wave function and most realistic nucleon-nucleon potentials predict nearly the same D_2 value), and the result derived from the tensor analyzing power measurements[11] is in good agreement with the expected value. Based on this experience we believe that accurate determinations of D_2 are also possible for (d,t) reactions.

III. EXPERIMENTAL DETAILS

The tensor analyzing power measurements were carried out using the deuteron beam from the University of Wisconsin Lamb-shift polarized ion source.[12] After being accelerated and momentum analyzed by a 90° bending magnet, the incident beam was focused through 1 mm wide by 2 mm high rectangular slits located about 15 cm upstream of the target. An automatic feedback system was used to keep the beam centered on the slits. The targets were enriched, self-supporting foils with thicknesses of from 1 to 4 mg/cm^2.

Reaction products were detected by an array of four ΔE-E counter telescopes located to one side of the beam. An on-line particle identification computer program was used to distinguish the various reaction products. For the experiments at 6.0 and 7.5 MeV the thickness of the ΔE detectors was approximately 60 μm, while at the higher energies detectors of approximately 100 μm were used. Figure 1 shows a typical particle identification spectrum for 6 MeV deuterons on ^{119}Sn. This spectrum gives the number of counts as a function of a parameter calculated from the energies deposited in the ΔE and E detectors.[13] In spite of the fact that the ratio of deuterons to tritons is large, the triton peak is well separated.

A typical triton energy spectrum for the reaction ^{118}Sn(d, t) at 12.0 MeV is shown in Fig. 2. Note that the various triton peaks are well resolved and virtually free of background. For ^{91}Zr, ^{119}Sn, and ^{208}Pb the peaks of interest were easily resolved, since in all cases the states are separated by at least 300 keV.

Beam integration was accomplished by observing deuteron elastic scattering with a pair of monitor detectors located symmetrically to the left and right of the beam at an angle of 13.1°. To a good approximation, the count rate in the monitor detectors is independent of the beam polarization, since the elastic scattering analyzing powers are essentially zero at this angle.

The procedure used to determine the tensor analyzing powers is similar to that described by Rohrig and Haeberli.[14] The method involves obtaining relative measurements of the polarized-beam cross section for a variety of polarization states of the incident beam. The beam polarization was monitored continuously during the experiments by a polarimeter located downstream of the target. For the measurements at 12.0 and 12.3 MeV the polarimeter described in Ref. 15 was used. For the experiments at lower energies, which were performed somewhat later, we used a more accurate polarimeter.[16]

The measured tensor analyzing powers will be presented in a number of subsequent figures. In all cases, the error bars shown in the figures include contributions from counting statistics, from uncertainties in background subtraction and from the statistical uncertainty in the determination of the beam polarization. In addition to the displayed errors, the measurements are subject to an overall normalization uncertainty which is estimated to be 10% for the measure-

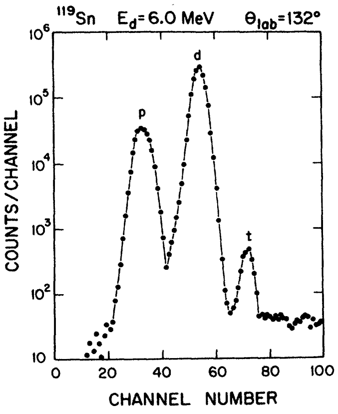


FIG. 1. A typical particle identification spectrum for 6 MeV deuterons on ^{119}Sn.

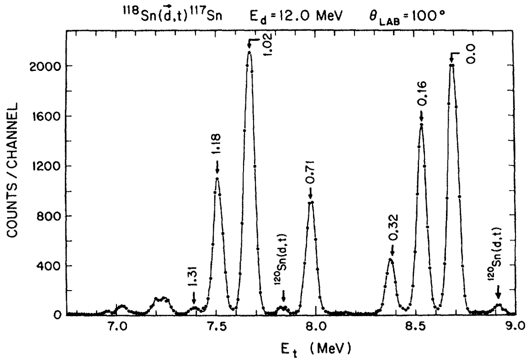


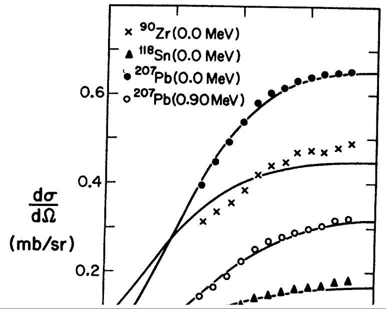
FIG. 2. A typical triton energy spectrum for the reaction ^{118}Sn(d,t) at 12 MeV. The peaks are identified by the excitation energy of the residual nucleus.

ments at 12.0 and 12.3 MeV and 2% for the measurements at lower energies.[16] The analyzing powers presented here are defined according to the Madison convention.[17]

IV. RESULTS

A. Sub-Coulomb measurements

As discussed in Sec. II, it is expected that the most reliable determinations of D_2 are obtained



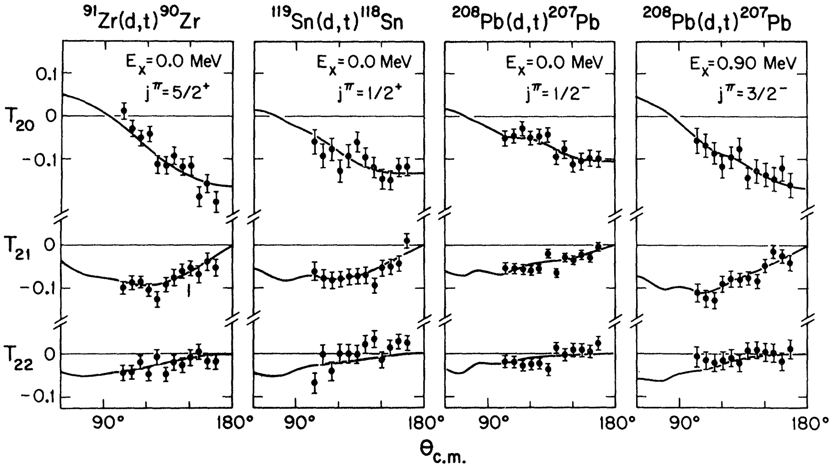


FIG. 4. Measurements of the tensor analyzing powers for sub-Coulomb $(\vec{d},t)$ reactions on ^{91}Zr, ^{119}Sn, and ^{208}Pb. The curves are DWBA calculations corresponding to the D_2 values listed in Table I.

that in all four cases the χ^2/N value is close to 1.0, indicating that the DWBA calculations reproduce the measurements as accurately as can be expected. The uncertainties in D_2 quoted in Table I reflect only the statistical errors in the analyzing power measurements. Sources of systematic error in the determination of D_2 will be considered below. It is encouraging to note that the results obtained from the four transitions are in reasonably good agreement.

rors in the measurement of the beam polarization lead to an uncertainty of approximately 2% (see Ref. 16) in the overall normalization of the measured tensor analyzing powers. The corresponding uncertainty in D_2 is ±0.0056 fm^2. The choice of optical model potentials also affects the value of D_2. From Table II we see that, for a given transition, changing potentials produces variations of typically ±0.003 fm^2 in D_2. Somewhat arbitrarily, the uncertainty associated with the

TABLE II. Values of D_2 obtained with various deuteron and triton optical model potentials. The D_2 values are in fm^2.

Deuteron potential	Triton potential	$^{91}\text{Zr}(\frac{5}{2}^+)$	$^{119}\text{Sn}(\frac{1}{2}^+)$	$^{208}\text{Pb}(\frac{1}{2}^-)$	$^{208}\text{Pb}(\frac{3}{2}^-)$
Ref. 18	Ref. 22	−0.260	−0.302	−0.278	−0.278
Ref. 19	Ref. 22	−0.258	−0.302	−0.277	−0.278
Ref. 20	Ref. 22	−0.260	−0.304	−0.283	−0.281
Ref. 18	Ref. 23	−0.262	−0.301	−0.287	−0.282
Ref. 18	Ref. 24	−0.259	−0.305	−0.279	−0.279
Ref. 21	Ref. 24	−0.253	−0.296	−0.276	−0.275
Standard deviation:		0.003	0.003	0.004	0.002

increasing energy. This is illustrated in Fig. 5 which shows the cross section measurements for $^{119}\text{Sn}(d, t)$ at $E_d = 6.0$, 7.5, and 9.0 MeV. At 6 MeV the cross section is small and backward peaked. However, at 7.5 MeV the peak cross section occurs at approximately 90°, while at 9 MeV the

effects were neglected are shown for the $^{118}\text{Sn}(d, t)$ transitions (dashed curves in Fig. 7). For all of the other transitions, the calculations which include only the S state lead to tensor analyzing powers which are too small to be seen in the figures, typically two orders of magnitude smaller

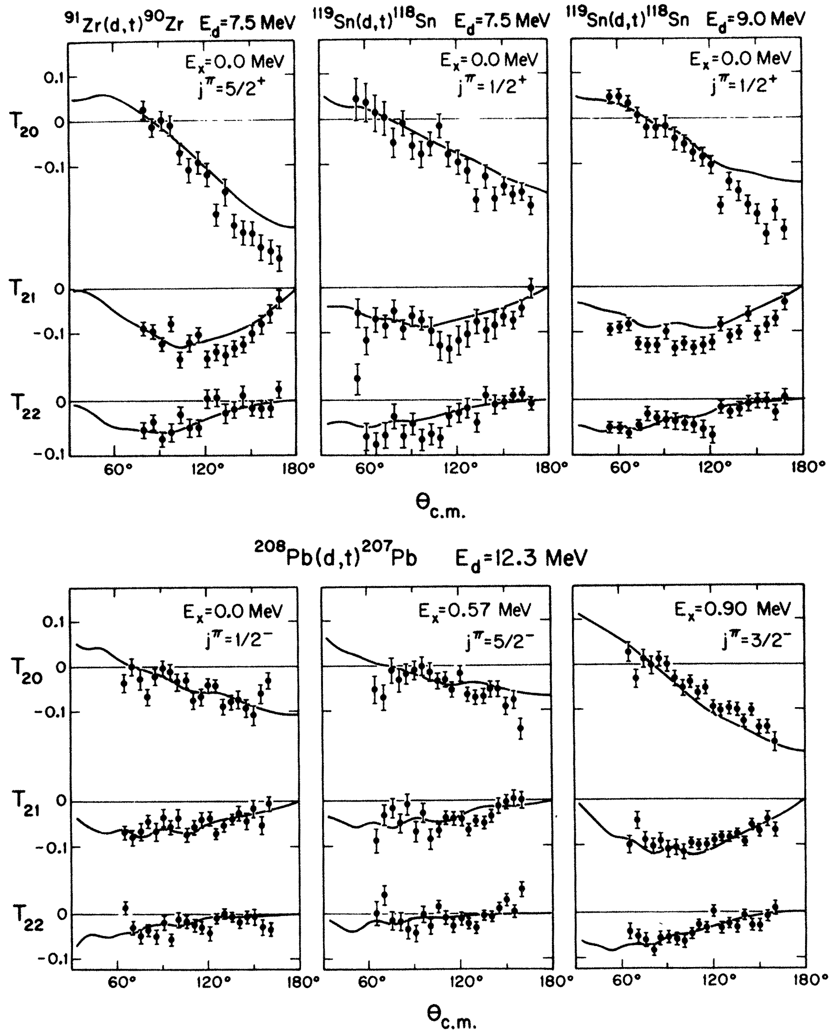


FIG. 6. Measurements of the tensor analyzing powers for $(\vec{d},t)$ reactions on ^{91}Zr, ^{119}Sn, and ^{208}Pb for energies above the Coulomb barrier. The curves are DWBA calculations corresponding to $D_2 = -0.279$ fm^2.

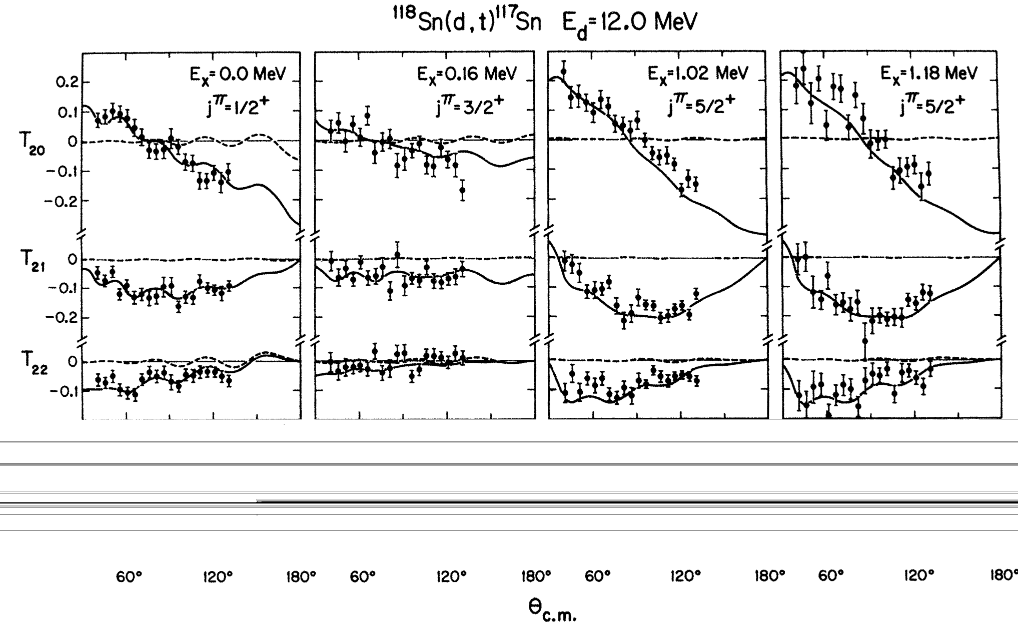


FIG. 7. Measurements of the tensor analyzing powers for ^{118}Sn$(\vec{d},t)^{119}$Sn. The solid curves are DWBA calculations corresponding to $D_2 = -0.279$ fm^2, while the dashed curves are calculations which include only the S state.

TABLE III. Best-fit D_2 values for the (d,t) measurements obtained at energies above the Coulomb barrier.

Target	E_d (MeV)	E_x (MeV)	j^π	D_2 (fm^2)	χ^2/N
^{91}Zr	7.5	0.0	$\frac{5}{2}^+$	-0.331 ± 0.009	1.55
^{118}Sn	12.0	0.0	$\frac{1}{2}^+$	-0.278 ± 0.010	1.15
^{118}Sn	12.0	0.16	$\frac{3}{2}^+$	-0.270 ± 0.025	1.54
^{118}Sn	12.0	1.02	$\frac{5}{2}^+$	-0.228 ± 0.006	2.06
^{118}Sn	12.0	1.18	$\frac{5}{2}^+$	-0.238 ± 0.009	1.60
^{119}Sn	7.5	0.0	$\frac{1}{2}^+$	-0.360 ± 0.013	1.13
^{119}Sn	9.0	0.0	$\frac{1}{2}^+$	-0.396 ± 0.009	1.73
^{208}Pb	12.3	0.0	$\frac{1}{2}^-$	-0.254 ± 0.013	1.72
^{208}Pb	12.3	0.57	$\frac{5}{2}^-$	-0.328 ± 0.020	1.98
^{208}Pb	12.3	0.90	$\frac{3}{2}^-$	-0.233 ± 0.006	1.29

transitions, and that consequently, the derived D_2 values are most accurate in these cases. Our experimental results support this argument. For the sub-Coulomb reactions, the DWBA fits to the data are of good quality, and the D_2 values obtained from different transitions (see Table I) are in reasonably good agreement. On the other hand, the D_2 values for the measurements at higher

finite-range effects. Finally, systematic errors in the determination of D_2 could result from the neglect of multistep processes in the DWBA calculation. For sub-Coulomb energies, conventional multistep processes (e.g., inelastic excitation of the target followed by neutron transfer) are probably unimportant since the coupling between various reaction channels is weak. Of somewhat

greater concern is the effect of distortion (i.e., virtual excitation) of the deuteron and triton by the Coulomb field of the nucleus. In the DWBA calculations one assumes that at the point of transfer the internal wave functions of the deuteron and triton are just the free-projectile wave functions. Of course, distortion of the projectile wave functions will affect the determination of D_2 only to the extent that the effects are spin dependent. Recently, Tostevin and Johnson[26] have calculated the effects of deuteron distortion for sub-Coulomb (d,p) reactions and found that the tensor analyzing powers change by only a few percent. Thus one might expect that these effects will be small for (d,t) reactions as well.

As noted above, the consistency of our results is quite poor for the reactions which have energies above the Coulomb barrier. To some extent, this is to be expected. However, it is disturbing that the extracted D_2 values change so rapidly with increasing energy. In particular, we note that

It is clear that additional theoretical work on various aspects of this subject would be valuable. In particular, it would be of interest to determine whether including finite-range effects, the effects of tensor forces, or the effects of projectile distortion in the DWBA calculations would lead to improved agreement between experiment and theory. Another important question which has not yet been answered is whether triton wave functions obtained from various nucleon-nucleon potentials lead to different D_2 values. In addition, it would be interesting to determine whether D_2 might be sensitive to the presence of three-body forces in the triton.

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