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Determination of the triton D-state parameter D_2 from sub-Coulomb $(\vec{d},t)$ measurements

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Measurements of the tensor analyzing powers for sub-Coulomb $(\vec{d},t)$ reactions on ^{91}Zr at $E_d = 5$ MeV and ^{147}Sm at $E_d = 6.5$ MeV are presented. The measurements are analyzed to obtain values of the triton D-state parameter D_2. The results are found to be in good agreement with the D_2 values derived from previous sub-Coulomb measurements, and lend support to the contention that analyzing power measurements for sub-Coulomb $(\vec{d},t)$ reactions provide reliable information about the D-state components.

NUCLEAR REACTIONS ^{91}Zr$(\vec{d},t)$, $E_d = 5.0$ MeV, ^{147}Sm$(\vec{d},t)$, $E_d = 6.5$ MeV; measured polarization parameters $T_{20}(\theta)$, $T_{21}(\theta)$, $T_{22}(\theta)$; deduced D_2. Enriched targets, DWBA analysis.

It is well known that the triton wave function contains D-state terms in addition to the dominant S-state component, and that it is possible to observe effects of the D-state components in a (d,t) reaction. In particular, it has been shown[1] that measurements of the tensor analyzing powers for a (d,t) reaction are sensitive to the presence of the D-state terms. Such measurements thus provide a means for obtaining information about the D-state components of the triton wave function.

In order to extract quantitative information from the measurements, one uses the distorted-wave Born approximation (DWBA). In addition, it is common practice to employ the local-energy approximation[2] (LEA). Within the context of DWBA and LEA, the D-state effect depends on the value of a single parameter, D_2. This parameter is closely related to the asymptotic D- to S-state ratio for the $^3\mathrm{H} \rightarrow n + d$ portion of the triton wave function.[3,4] A rigorous definition of D_2 is given in Refs. 1 and 5. It is straightforward to extract an empirical value of D_2 from measurements of the tensor analyzing powers, since the analyzing powers are, to a good approximation, directly proportional to D_2.

It has been argued[5] that the most reliable determinations of D_2 are those obtained from sub-Coulomb reactions. Sub-Coulomb energies are preferred because the DWBA calculations are most accurate in this case.[5,6] Tensor analyzing power measurements have been reported for a large number of (d,t) reactions; however, the only sub-Coulomb measurements are those of Ref. 5. The results given in Ref. 5 lend support to the idea that sub-Coulomb measurements lead to the most reliable values of D_2. It is found that sub-Coulomb measurements for different targets (^{91}Zr and ^{119}Sn at $E_d = 6$ MeV and ^{208}Pb at $E_d = 10$ MeV) consistently give the same value of D_2, whereas measurements at higher energies often lead to D_2 values which differ considerably from the average. It is also found[5] that in the sub-Coulomb cases the DWBA calculations do a much better job of reproducing the shape of the analyzing power angular distributions.

The overall best fit value of D_2 derived from the sub-Coulomb measurments of Ref. 5 is -0.279 ± 0.012 fm^2. On the other hand, the current best theoretical value of D_2, obtained by solving the Faddeev equations and extracting the asymptotic normalization constants of the resulting triton wave function,[3,4] is -0.24 fm^2.

In Ref. 5 it was observed that while the sub-Coulomb measurements give consistent results, the situation changes drastically for higher energies. For example, it was found that for ^{91}Zr and ^{119}Sn, the deduced values of D_2 increased in magnitude by more than 20% as the energy was changed from 6.0 to 7.5 MeV. For ^{208}Pb, increasing the energy led to smaller D_2 values. While it is expected that the method for finding D_2 will become less reliable at higher energies, it is disturbing that the extracted values of D_2 change so rapidly, and consequently, this behavior raises some question about the reliability of the sub-Coulomb results. One way to resolve this question is to obtain additional measurements at energies below those of Ref. 5, and see whether the resulting D_2 values are consistent with the result obtained in Ref. 5.

In this paper we present new measurements of the tensor analyzing powers for sub-Coulomb (d,t) reactions on ^{91}Zr and ^{147}Sm. The ^{91}Zr measurements are for $E_d = 5$ MeV (the lowest energy used in Ref. 5 was 6 MeV). For ^{147}Sm the bombarding energy was 6.5 MeV, which is farther below the Coulomb barrier than any case previously studied. Both reactions involve fairly strong single particle transitions (only the ground state transition is analyzed in each case) which have Q values close to zero. In each case the angular momentum transfer is $j=l+\frac{1}{2}$ ($j^\pi=\frac{5}{2}^+$ for ^{91}Zr and $\frac{7}{2}^-$ for ^{147}Sm), which leads to relatively large tensor analyzing powers.

The measurements were acquired using the tensor-polarized deuteron beam from the University of Wisconsin crossed-beam polarized ion source.[7] The targets consisted of isotopically enriched self-supporting foils 2 mg/cm^2 thick. Reaction products were detected by an array of $\Delta E-E$ counter telescopes located to one side of the beam. In the case of ^{91}Zr two telescopes with ΔE detectors approximately 50 μm thick were used, while for ^{147}Sm we used four telescopes with 60 μm thick ΔE detectors. An online particle-identification program was used to separate tritons from other reaction products. The counting rate in the experiment was limited by the computer data processing program to approximately 7000 events/sec. Beam currents on target were typically 35 nA.

To measure the tensor analyzing powers the spin alignment axis of the beam was oriented (by setting a Wein filter just after the ion source) to make one of the beam moments (t_{20}, t_{21}, or t_{22}) nonzero. During each run the sign of the tensor polarization was reversed every 0.25 sec by switching RF transitions at the source, and the corresponding spectra were routed into separate areas of the computer memory. The beam polarizations were determined by a polarimeter[8] located downstream of the scattering chamber.

The tensor analyzing power measurements are presented in Fig. 1. The error bars shown in the figure represent the statistical uncertainties in the measurements. In addition to the displayed errors, the measurements are subject to an overall normalization uncertainty of 2% (see Ref. 8).

The curves in Fig. 1 show the results of DWBA calculations obtained by using the LEA. The deuteron and triton optical model potentials of Refs. 9 and 10 were used in the calculations. For each transition the value of D_2 has been adjusted to obtain the best overall fit to the tensor analyzing power data, and the curves shown correspond to these best-fit values. The resulting D_2 values are -0.259 ± 0.014 fm^2 for ^{91}Zr and -0.288 ± 0.011 fm^2 for ^{147}Sm, where the quoted errors reflect the statistical uncertainties in the measurements. Further DWBA calculations show that the use of different optical model potentials leads to changes of at most 0.001 fm^2 in the extracted values of D_2.

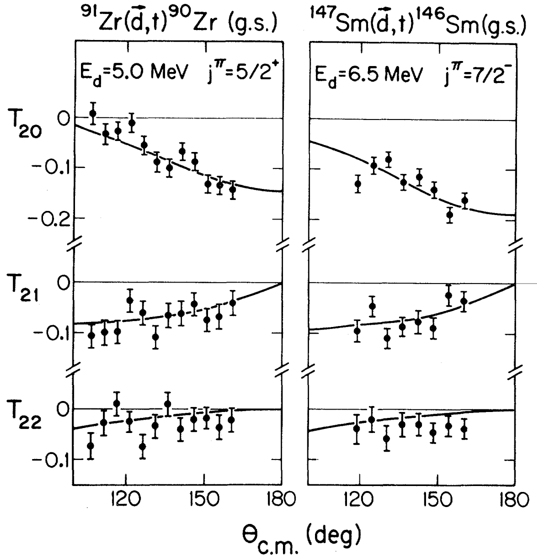

FIG. 1. Measurements of the tensor analyzing powers for ^{91}Zr(d,t) at $E_d=5.0$ MeV and ^{147}Sm(d,t) at $E_d=6.5$ MeV. The curves are DWBA calculations which include D-state effects. For each target the value of D_2 has been adjusted to obtain the best overall fit to the measurements.

The present D_2 results are seen to be in good agreement with the value -0.279 ± 0.012 fm^2 found in Ref. 5. This suggests that values of D_2 extracted from tensor analyzing power measurments are stable against variations in the bombarding energy, provided that the energy remains below the Coulomb barrier, and lends strong support to the contention that sub-Coulomb (d,t) reactions permit one to obtain reliable information about the D-state components of the triton wave function.

Finally it should be noted that the current discrepancy between the empirical and theoretical[3,4] values of D_2 might very well be a consequence of approximations which we use in the DWBA analysis of our measurements. In particular, finite-range effects and the effects of deuteron nucleus tensor forces, which are neglected in the present work and in Ref. 5, could easily produce a small non-negligible change in the calculated tensor analyzing powers. Calculations of these effects will be reported in a future publication.

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