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Observation of the Deuteron D-State Effects in (d, p) Reactions

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Angular distributions of the three tensor analyzing powers have been measured for (d,p) reactions on ^{52}Cr, ^{90}Zr, and ^{208}Pb. Distorted-wave calculations are inconsistent with the measurements if the deuteron D state is ignored. However, excellent agreement is obtained when the effects of the D state are included. We discuss the dependence of the tensor analyzing powers on incident deuteron energy, Q value, and angular momentum transfer.

The purpose of this Letter is to discuss the effects of the deuteron D state on (d,p) stripping reactions with polarized deuterons. Calculations[1,2] have shown that the cross section and vector analyzing power for (d,p) reactions are insensitive to the presence of the D state, and as a result the D state is usually neglected in the calculations.[3] However, the calculated tensor analyzing powers[4] (T_{20}, T_{21}, T_{22}) change substantially when the effects of the D state are included. Thus, measurements of the tensor analyzing powers provide the best available method for experimental observation of the deuteron D-state effects in (d,p) reactions. In this Letter we will report the first measurements[5] of all three tensor analyzing powers for (d,p) reactions on nuclei for which direct reaction theory is expected to be applicable. These measurements will be compared to calculations using the distorted-wave Born approximation (DWBA) with and without the effects of the deuteron D state.

In a previous Letter Brown *et al.*[6] found that inclusion of the D state resulted in improved agreement with measurements of T_{20} at 0°. However, the experiment of Ref. 6 was done with targets and energies for which compound-nucleus contributions are expected to be large,[7] and thus it is not surprising that the agreement of the DWBA calculations with the measurements was not quantitative.

In general, the tensor analyzing powers calculated by DWBA arise in part from the nuclear spin-dependent distortions and in part from the D-state effects. However, under special circumstances, the effects of the nuclear distortions can be quite small, and in these cases the influence of the D state should be especially evident. The effect of nuclear distortions on the tensor analyzing powers is expected to be small for transitions with $l_n = 0$,[8] and for all sub-Coulomb reactions.

Measurements for sub-Coulomb and $l_n = 0$ transitions are shown in Fig. 1. The dashed curves show the result of DWBA calculations which neglect the contributions from the deuteron D state [DWBA(S)]. The DWBA(S) analyzing powers are consistently found to be much smaller in magnitude than the measurements.

The analyzing powers which result when the D state is included in the calculations [DWBA($S+D$)] are shown by the solid curves in Fig. 1. These calculations were done using the approximation method suggested by Johnson and Santos.[9] In this approximation, the deuteron wave function is described by three parameters[10] which, for the present calculations, were determined from the Reid soft-core potential.[11] The proton optical-model potentials were taken from the work of Becchetti and Greenlees,[12] while the deuteron po-

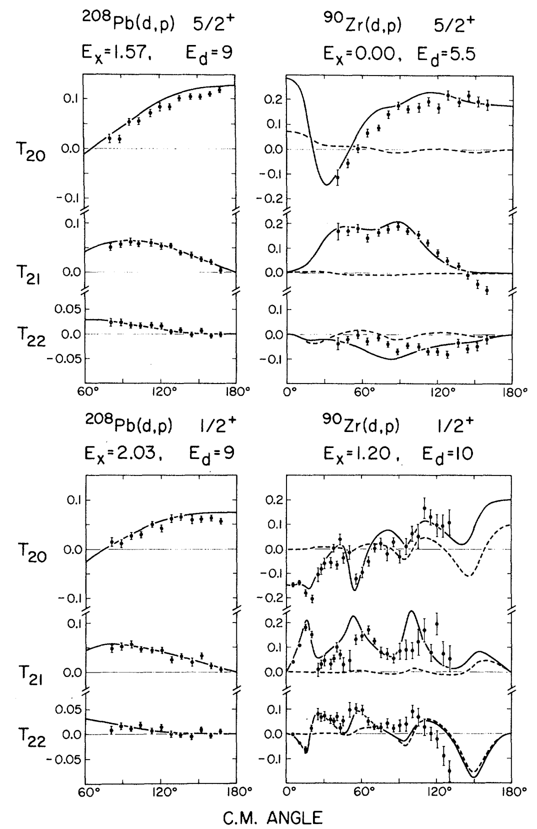

FIG. 1. Angular distributions of the tensor analyzing powers for (d,p) transitions to the 1.57-MeV and 2.03-MeV states of ^{209}Pb at a deuteron energy of 9 MeV, to the ground state of ^{91}Zr at an energy of 5.5 MeV, and to the 1.20-MeV state in ^{91}Zr at an energy of 10 MeV. Each transition is identified by the spin, parity, and excitation energy of the final state, and by the incident deuteron energy. The energies are given in MeV. The dashed curves show the result of DWBA calculations which neglect the deuteron D state, and the solid curves show the analyzing powers which result when the D state is included. The dashed curves are not shown for the ^{208}Pb$(d,p)^{209}$Pb transitions since the analyzing powers are smaller in magnitude than 0.01.

tentials, which are listed in Table I, were obtained from Lohr and Haeberli.[13] The neutron bound-state wave functions were determined in the usual manner.[14]

The results in Fig. 1 show clearly that consideration of the deuteron D state is important for a complete understanding of (d,p) reactions with polarized deuterons. The agreement of the DWBA$(S+D)$ calculations with the measurements is particularly accurate for the transitions to the two states in ^{209}Pb. For these transitions both the incident deuterons and the outgoing protons have energies far below the Coulomb barrier, and the

TABLE I. Parameters of the deuteron optical-model potentials. The notation is that of Ref. 12. The parameters V_R, W_{SF}, r_I, and a_I are listed in the table. The remaining parameters had the values $r_R=1.05$ fm, $a_R=0.86$ fm, $V_{so}=7.0$ MeV, $r_{so}=0.75$ fm, $a_{so}=0.50$ fm, and $r_c=1.30$ fm.

	V_R (MeV)	W_{SF} (MeV)	r_I (fm)	a_I (fm)
^{52}Cr	105.27	15.33	1.43	0.66
^{90}Zr	112.38	10.94	1.43	0.80
^{208}Pb	119.18	6.02	1.50	0.93

DWBA(S) predictions for the tensor analyzing powers are typically 2 orders of magnitude smaller than the measurements. The ^{90}Zr$(d,p)^{91}$Zr ground-state transition at 5.5 MeV is more sensitive to the nuclear distortions, since the incident deuterons are sub-Coulomb but the outgoing protons are not. The agreement between the measurements and the DWBA$(S+D)$ calculation is quite good, but not as accurate as for the transitions on ^{208}Pb. It is interesting to note that the qualitative features of the analyzing powers are independent of the target and the transferred angular momentum for all sub-Coulomb transitions shown. The measured tensor analyzing powers for the transition to the $l_n=0$ state in ^{91}Zr show a complicated angular dependence since the deuteron and proton energies are above the Coulomb barrier. The DWBA$(S+D)$ calculations agree well with the measurements, particularly at forward angles where DWBA is expected to be most accurate. From the results shown in Fig. 1, one can conclude that the DWBA$(S+D)$ predictions are most accurate where the influence of the nuclear spin-dependent distortions is small.

To this point we have considered transitions for which the effect of nuclear distortions is expected to be particularly small. We would now like to discuss the results for more typical (d,p) reactions. Figure 2 contains measurements and calculations for several transitions which will be used to demonstrate the systematics of the tensor analyzing powers for (d,p) reactions. All of the tensor analyzing powers exhibit an angular dependence which is more complicated than the simple oscillatory behavior which has been observed for the vector analyzing power.[15]

The DWBA(S) calculations shown in Fig. 2 do not agree with the measurements; the disagreement is most pronounced for T_{21}, where the calculations are an order of magnitude smaller than the

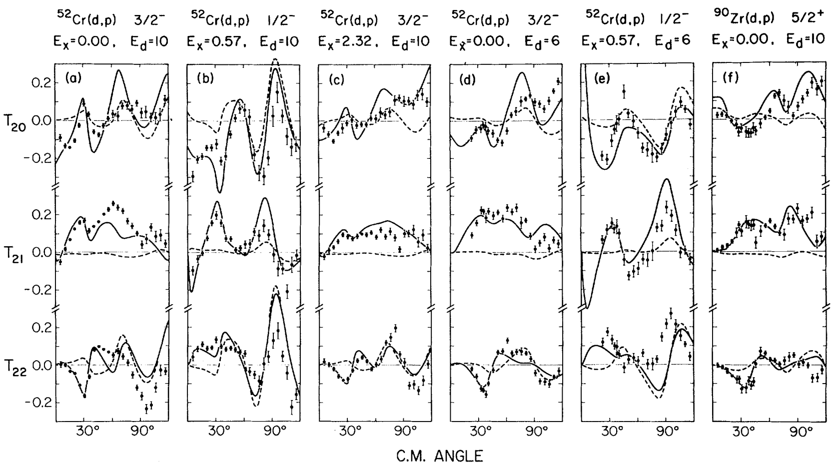

FIG. 2. Angular distributions of the tensor analyzing powers for (d,p) transitions to the ground, 0.57-MeV and 2.32-MeV states of ^{53}Cr and to the ground state of ^{91}Zr at a deuteron energy of 10 MeV, and to the ground and 0.57-MeV states of ^{53}Cr at an energy of 6 MeV. Each transition is identified by the spin, parity, and excitation energy of the final state, and by the incident deuteron energy. The energies are given in MeV. The dashed and solid curves are the same as in Fig. 1.

observed analyzing powers. Because of this, measurements of T_{21} are particularly useful in studies of the D-state effects in (d,p) reactions. The addition of the effects of the D state greatly improves the agreement for all transitions shown. The DWBA$(S+D)$ calculations are particularly accurate for T_{21} and T_{22} at forward angles. The calculations are not as satisfactory for T_{20} at forward angles, and hence the measurements of T_{20} at 0° (Refs. 6 and 7) do not provide the most reliable test of the deuteron D-state effects.

The DWBA$(S+D)$ calculations predict that the tensor analyzing powers depend strongly on the Q value of the reaction, whereas relatively little Q dependence is observed for the cross section and vector analyzing power.[15] Transitions to states in ^{53}Cr which differ only in Q value are shown in Figs. 2(a) and 2(c); the Q values for the two transitions are 5.72 and 3.40 MeV, respectively. The DWBA$(S+D)$ calculations for these two transitions show similar features, but the magnitude of the analyzing powers tends to be smaller for the transition with lower Q value. This Q dependence is verified by the measurements.

For energies above the Coulomb barrier the tensor analyzing powers show little dependence on the incident deuteron energy. This can be seen by comparing the tensor analyzing powers for the transitions to the ground state [Figs. 2(a) and 2(d)] and the 0.57-MeV state [Figs. 2(b) and 2(e)] of ^{53}Cr for deuteron energies of 10 and 6 MeV. However, when the deuteron energy is below the Coulomb barrier the analyzing powers are smooth functions of angle rather than complicated oscillatory functions. In spite of this, the analyzing powers show some common features above and below the Coulomb barrier. For the ^{90}Zr$(d,p)^{91}$Zr ground-state transition, the following characteristics are observed in the tensor analyzing powers at 5.5 MeV (Fig. 1) and at 10 MeV [Fig. 2(f)]: The T_{20} measurements cross zero near 55° and are large and positive at back angles; T_{21} is large and positive from 30° to 110°; T_{22} is substantially smaller in magnitude than T_{20} and T_{21} over most of the angular range.

A particularly interesting feature of the measurements is the behavior of T_{22} at forward angles. For all transitions with $j_n = l_n + \frac{1}{2}$ [Figs. 2(a), 2(c), 2(d), and 2(f) and the $l_n = 0$ transition on ^{90}Zr in Fig. 1] T_{22} shows a sharp negative dip in the region of the first maximum in the differential cross section, and a zero crossing which occurs very near the first minimum in the cross section. This feature is very well reproduced by the DWBA$(S+D)$ calculations. The negative dip in T_{22} has not been observed for transitions with $j_n = l_n - \frac{1}{2}$, and thus it may be useful in determining j_n values of (d,p) transitions.

Measurements and DWBA calculations of the tensor analyzing powers have been presented for a total of ten (d,p) transitions. In all cases the DWBA calculations fail to resemble the measurements when the deuteron D state is neglected.

When the effects of the D state are included, the resulting analyzing powers agree well with the data. The agreement of the DWBA($S+D$) calculations with the measurements is generally best when the spin-orbit potentials make a small contribution to the tensor analyzing powers (for sub-Coulomb transition, for the $l_n=0$ transition, and for T_{21} for all transitions). This suggests that the less accurate agreement in other cases may result from the use of incorrect potentials, rather than from incorrect treatment of the D state. Other possible sources of error in the calculations arise from the neglect of tensor forces in the deuteron optical-model potential,[16] and from calculational errors resulting from the approximation method used.[9]

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Mass Excess and Low-Lying Level Structure of ^{14}B

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The mass excess of ^{14}B has been measured to be 23.657 ± 0.030 MeV using the reaction ^{14}C(^{7}Li, ^{7}Be)^{14}B at $E(^7\mathrm{Li})=52$ MeV; this shows that ^{14}B is bound by nearly 1 MeV against neutron emission. Five excited states were also observed at 0.74 ± 0.04, 1.38 ± 0.03, 1.82 ± 0.06, 2.08 ± 0.05, and 2.97 ± 0.04 MeV. The low-lying level structure of ^{14}B was found to be similar to the known negative-parity spectrum of ^{12}B.

The mass of ^{14}B has presented an intriguing puzzle for a number of years. In 1966, Garvey and Kelson[1] predicted ^{14}B to be nucleon stable by ~400 keV. Although they considered their result to be equivocal, a short time later the nucleus was indeed observed by Poskanzer *et al.*[2] to be