Small-Angle Tensor Analyzing Power of (d, p) Reactions and Deuteron D-State Effects

R. C. Brown, A. A. Debenham, G. W. Greenlees,* J. A. R. Griffith, O. Karban, D. C. Kocher,† and S. Roman
Department of Physics, University of Birmingham, Birmingham, England
(Received 7 September 1971)

The tensor analyzing power of (d,p) transitions on ^{9}Be, ^{12}C, ^{16}O, ^{19}F, ^{25}Mg, ^{28}Si, and ^{40}Ca was measured at $E_d = 12.3$ MeV for $\theta_{\text{lab}} = 0 - 50°$. The reactions studied included orbital angular-momentum transfers $l = 0, 1, 2, 3$. Large values of T_{20} were observed, negative near 0° for most transitions. Distorted-wave calculations show agreement with the data only when a D-state contribution is included in the deuteron internal wave function.

In previous measurements in this laboratory,[1] large negative values of the tensor analyzing power T_{20} were observed for (d,p) reactions on ^{9}Be, ^{12}C, and ^{28}Si at small reaction angles including 0°. Calculations showed that the observed behavior at small angles could not be reproduced by conventional distorted-wave theory[2] irrespective of the choice of the distorting potentials in the incoming and outgoing channels. In these calculations the transition matrix elements used contained a pure S-state internal wave function for the deuteron. It has been suggested by Johnson[3] that (d,p) tensor analyzing powers should be affected by the deuteron D-state contribution. Calculations by Delic and Robson[4] and by Santos[5] indicated that the values of T_{20} at reaction angles near 0° were particularly sensitive to the D-state admixture.

The present experiment was undertaken to study the tensor analyzing power of (d,p) reactions at small reaction angles. Several target nuclei were chosen in order to investigate a range of angular-momentum transfers l and j.

The measurements were made using the 12.3-MeV tensor polarized beam[6] from the University of Birmingham radial-ridge cyclotron. The tensor polarization is specified by the parameter[7] t_{20}; the other tensor components of the beam are given by $t_{22} = (\frac{3}{2})^{1/2} t_{20}$ and $t_{21} = 0$. The ion source was switched at a frequency of 6 Hz between polarized and unpolarized beams. In the main scattering chamber the reaction protons were detected by three pairs of solid-state detector telescopes placed at equal angles to the left and right of the incident beam direction. The scattering chamber could be rotated about the beam axis, so that alternate runs with the chamber in horizontal and vertical positions allowed the analyzing powers T_{20} and T_{22} to be determined separately. The tensor polarization of the beam was monitored continuously in a ^{3}He gas-cell polarimeter placed downstream of the main scattering chamber and using the reaction $^3\text{He}(d,p)^4\text{He}$ at an angle of 0° for which the analyzing power T_{20} is known.[8] The ^{3}He tensor polarimeter could not be operated

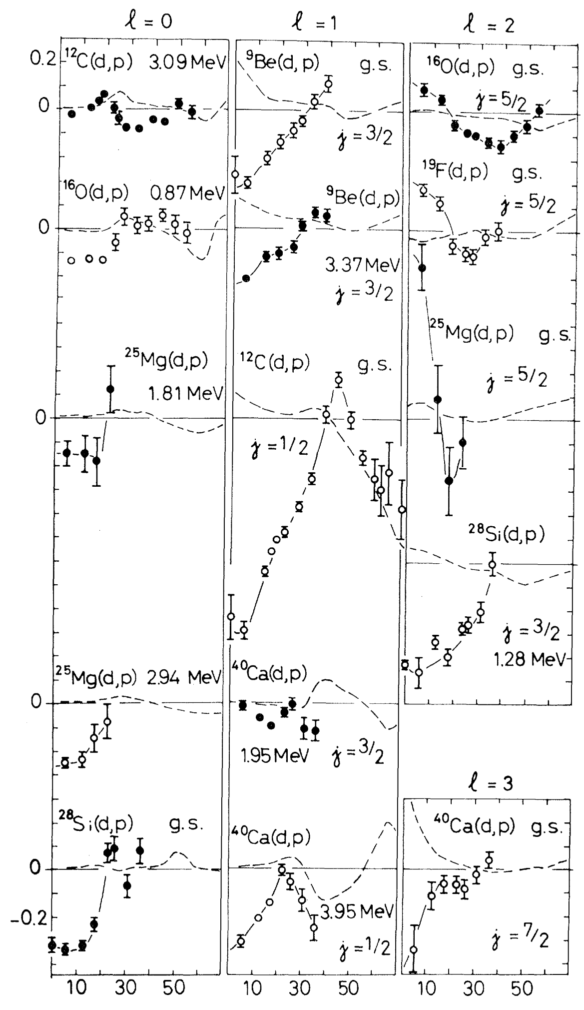

FIG. 1. Tensor analyzing power T_{20} for (d,p) reactions at $E_d = 12.3$ MeV. Dashed lines are DWBA predictions for purely S-state internal deuteron wave function. Continuous lines were drawn through the experimental points.

when data were taken at 0° in the main chamber; for these runs t_{20} was taken as a mean of the readings before and after the run assuming steady running conditions of the source. The 0° points are, therefore, subject to a slight additional uncertainty.

Results were obtained for fifteen (d,p) transitions on ^{9}Be, ^{12}C, ^{16}O, ^{19}F, ^{25}Mg, ^{28}Si, and ^{40}Ca targets with transferred angular momenta $l=0,1,2,3$ and $j=\frac{1}{2},\frac{3}{2},\frac{5}{2},\frac{7}{2}$. The results for T_{20} are presented in Fig. 1.[9] Of particular interest are the large negative values of T_{20} at angles near 0° for a number of transitions. $T_{20}(0°)$ is typically about -0.3 but it reaches -0.46 for ^{28}Si$(d,p)^{29}$Si (first excited state, $l=2$, $j=\frac{3}{2}$) and -0.89 for ^{12}C$(d,p)^{13}$C (ground state, $l=1$, $j=\frac{1}{2}$). Notable exceptions to this behavior are shown by the $l=2$, $j=\frac{5}{2}$ transitions in ^{16}O, ^{19}F, and ^{25}Mg for which T_{20} near 0° is large and positive. This apparent dependence of the sign of $T_{20}(0°)$ upon the j value has been only observed for $l=2$; for $l=1$ transitions $T_{20}(0°)$ is negative for both $j=\frac{1}{2}$ and $\frac{3}{2}$.

TABLE I. Comparison with DWBA. The experimental $T_{20}(0°)$ data are mean values of results for 0° and 5°; the uncertainties are statistical only.

l, j[a]	Reaction	E_x (MeV)	$T_{20}(0°)$ Expt.	$T_{20}(0°)$ DWBA S+D - State	$T_{20}(0°)$ DWBA S - state only
0, $\frac{1}{2}$	^{12}C(d, p)^{13}C	3.09	-0.028 ± 0.012		+0.004
0, $\frac{1}{2}$	^{16}O(d, p)^{17}O	0.87	-0.142 ± 0.012		+0.015
0, $\frac{1}{2}$	^{24}Mg(d, p)^{25}Mg	0.58		-0.21[b]	
0, $\frac{1}{2}$	^{25}Mg(d, p)^{26}Mg	1.81	-0.156 ± 0.056		-0.002
0, $\frac{1}{2}$	^{25}Mg(d, p)^{26}Mg	2.94	-0.254 ± 0.019		-0.016
0, $\frac{1}{2}$	^{28}Si(d, p)^{29}Si	g.s.	-0.33 ± 0.02		+0.0004
1, $\frac{1}{2}$	^{12}C(d, p)^{13}C	g.s.	-0.891 ± 0.033	-0.838[c]	-0.088
1, $\frac{1}{2}$	^{40}Ca(d, p)^{41}Ca	3.95	-0.306 ± 0.028	-0.36[b]	-0.006
1, 3/2	^{9}Be (d, p)^{10}Be	g.s.	-0.299 ± 0.026		+0.269
1, 3/2	^{9}Be (d, p)^{10}Be	3.37	-0.202 ± 0.016		+0.122
1, 3/2	^{40}Ca(d, p)^{41}Ca	1.95	-0.017 ± 0.023	-0.13[b]	+0.112
2, 3/2	^{28}Si(d, p)^{29}Si	1.28	-0.434 ± 0.012	-0.39[b]	+0.060
2, 5/2	^{16}O(d, p)^{17}O	g.s.	$+0.098 \pm 0.032$		+0.007
2, 5/2	^{19}F(d, p)^{20}F	g.s.	$+0.171 \pm 0.030$		-0.035
2, 5/2	^{24}Mg(d, p)^{25}Mg	g.s.		+0.19[b]	
2, 5/2	^{25}Mg(d, p)^{26}Mg	g.s.	$+0.65 \pm 0.11$		+0.065
3, 7/2	^{40}Ca(d, p)^{41}Ca	g.s.	-0.34 ± 0.13	-0.52[b]	+0.437

[a]The l and j values given are values used in DWBA calculations.
[b]Ref. 13.
[c]Ref. 14.

Distorted-wave calculations were carried out in the S-state approximation[2] for all the observed transitions. The distorting potentials for the incoming channel were taken from optical-model analyses of deuteron elastic-scattering data,[10] and for the outgoing channel the proton optical-model parameters of Becchetti and Greenlees[11] were used. This procedure was used in previous work in describing the (d,p) cross section and vector analyzing power for a number of transitions.[12] The predictions for T_{20} are shown by the dashed lines in Fig. 1; it is seen that the measurements are not reproduced even qualitatively. Calculations showed that no changes in optical-model parameters could improve the fit to the T_{20} data at small angles. All distorted-wave predictions included finite-range and nonlocality corrections, but their effect was insignificant.

To estimate the possible deuteron D-state contribution to the tensor analyzing power, the plane-wave approximation of Johnson[3] was used. The plane-wave values for $T_{20}(0^\circ)$ are always ≤ 0 and for the cases considered here the predicted $T_{20}(0^\circ)$ was about -0.2. The plane-wave approximation is expected[3] to underestimate the magnitude of T_{20}; obviously it cannot account for the observed j dependence in the sign of $T_{20}(0^\circ)$ for $l=2$ transitions.

Some distorted-wave calculations for (d,p) reactions including the deuteron D state have been made by Johnson and Santos[13] and by Delic.[14] In Table I the $T_{20}(0^\circ)$ values obtained in these calculations are compared with the present experimental results. Calculations corresponding to the measurements were not available for all cases and, since the predictions are not expected to be particularly sensitive to the target mass number or the reaction Q value, comparison is made in some cases for similar transitions in neighboring nuclei. The agreement in Table I is impressive; the change of sign observed experimentally for $l=2$, $j=\frac{5}{2}$ transitions is reproduced and the magnitudes predicted are in general close to the measured values.

The small-angle T_{20} analyzing powers of (d,p) reactions presented here provide strong evidence of the need to include a D-state component in the deuteron wave function. Measurements of this type along with a more complete analysis may offer the possibility of a quantitative assessment of the magnitude of the D-state contribution.

We wish to thank Dr. R. C. Johnson and Dr. G. Delic, who kindly made results of their calculations available to us prior to publication.

*Science Research Council Senior Visiting Fellow on leave from the University of Minnesota, Minneapolis, Minn. 55455.

†Present address: Oak Ridge National Laboratory, Oak Ridge, Tenn. 37830.

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