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Tensor Analyzing Power in *d-p* Scattering at Backward Angles for Deuteron Energies 0.3 to 2.3 GeV

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The tensor analyzing power T_{20} for d-p elastic scattering at or near $\theta_{\mathrm{c.m.}} = 180°$ has been measured at sixteen deuteron beam energies between 0.3 and 2.3 GeV. In marked disagreement with earlier work, large negative values ($|T_{20}| > 0.6$) are found at all energies in this range, with a dip to $T_{20} = -1.25$ at $T_d = 0.5$ GeV. The present results are compared with various model calculations.

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The elastic backward scattering of protons by deuterons has proven to be a rich source of information. At low energies (<300 MeV) it is sensitive to the deuteron wave function for small relative neutron-proton momentum and to nucleon rescattering mechanisms. At higher energies pion production channels open up, and the reaction mechanism is expected to be dominated by the production of Δ(1236) in intermediate states. Other contributions have also been postulated, such as N^* components of the deuteron wave function.[1] In fact, the energy dependence of the backward elastic scattering cross section $\sigma(180°)$ shows a bump in the region $0.4 < T_p < 1.0$ GeV, which is inconsistent with single-neutron exchange (see Komarov *et al.*,[2] for example). This bump was accounted for by various higher-order corrections, including a $pp \to d\pi$ rescattering mechanism,[3] or by peculiar structure in the deuteron wave function.[4]

Igo *et al.*[5] have measured at the Argonne zero gradient synchrotron the tensor analyzing power T_{20} near $\theta_{\mathrm{c.m.}} = 180°$. The values reported at $T_d = 0.8$, 1.6, and 2.0 GeV are all compatible with zero. The result at 0.8 GeV is especially surprising in view of the large negative values expected for the dominant one-nucleon exchange.[6] As a result, further theoretical efforts[7-11] have been made to explain these results.

With the polarized deuteron beam of Saturne 2, we have measured $T_{20}(180°)$, from 0.3 to 2.3 GeV. In the following paragraphs, we discuss the results of our experiment and their comparison with various calculations.

The polarized deuterons were produced by an atomic beam source[12] in which three radio-frequency transitions were cycled in successive beam pulses in order to produce different populations of spin states. The beam vector and tensor polarizations are defined by

$$\rho_{10} = \left(\frac{3}{2}\right)^{1/2} \left(\frac{M_+ - M_-}{M_+ + M_- + M_0}\right),$$

$$\rho_{20} = \left(\frac{1}{2}\right)^{1/2} \left(\frac{M_+ + M_- - 2M_0}{M_+ + M_- + M_0}\right),$$

where M_+, M_-, and M_0 are the number of deuterons in the +1, −1, and 0 spin states. Subsequent beam transport elements directed the low-energy (380-keV) deuteron beam either into the injector linac or into a low-energy polarimeter which consisted of a deuterated titanium target and semiconductor detectors at 0°, +120°, and −120° counting protons from the reaction $d(d,p)t$. The spherical tensor polarization ρ_{20} (quantization axis vertical) was determined by comparing counting rates in the 0° detector for the various spin states; the 0° cross section depends only on ρ_{20} through

$$\frac{d\sigma}{d\Omega}(0^\circ)=\left(\frac{d\sigma}{d\Omega}(0^\circ)\right)_{\text{unpol}}[1-\tfrac{1}{2}\rho_{20}T_{20}(0^\circ)].$$

The effective tensor analyzing power $T_{20}(0^\circ) = -0.75$ is calculated from an R-matrix fit to the low-energy four-nucleon-system data.[13] During the course of the experiment the beam polarization was measured repeatedly and found to be very stable; the value measured, $\rho_{20}=0.52$, is 76% of the maximum possible from the ion source. A theoretical study of depolarization effects during the acceleration and the extraction of deuterons in Saturne 2 has been achieved.[14] The calculations show neither intrinsic nor first-order resonances for deuterons in the energy range of Saturne. However, there is one second-order resonance possibly excited during the extraction at a deuteron energy around 1600 MeV, but its width is estimated to be less than 1 MeV and its depolarization effect should be less than 10^{-3}, negligible compared with our statistical errors. Moreover an experimental study of the same type of depolarizing resonance has been performed with protons.[14] No depolarization was measured even though the effect is expected to be 10 times larger for protons than for deuterons. For all these reasons, a depolarization effect cannot explain the dip observed in T_{20} around 1400 MeV.

The d-p elastic scattering at or near $\theta_{\text{c.m.}} = 180^\circ$ was measured on the spectrometer SPES 4.[15] An angular acceptance of ±7 mrad in both the horizontal and the vertical was defined by a 20-cm-thick collimator at the spectrometer entrance. The detection system consisted of a hodoscope of 44 plastic scintillators, each covering a momentum bite of 0.2%, in the final focal plane. An array of seven scintillators placed in an intermediate focal plane provided time-of-flight information over a 16-m path; combined with the known magnetic rigidity this provided particle identification. The target was a 3.8-cm-thick cell filled with liquid hydrogen, and an identical empty cell was used for background measurements. The relative intensity in each beam pulse was measured independently by a secondary-emission monitor and an ionization chamber.

For $\theta_{\text{c.m.}}=180^\circ$ both the recoil proton and scattered deuteron appear at $\theta_{\text{lab}}=0^\circ$, the proton having about 70% and the deuteron 30% of the beam momentum. A 7° bending magnet between the target and spectrometer entrance separated the scattered particles from the incident beam. We observed both deuterons and protons. The deuteron peak corrected for the energy loss in the target was detected above an important background due to air and target-cell windows. This background was suppressed by target-empty subtraction [see Fig. 1(a)]. Deuterons were not detected at beam energies below 1 GeV, because the elastic peak became wider than the SPES 4 momentum acceptance, nor for energies above 1.6 GeV, because the laboratory cross section became too small. Concerning proton detection, at low beam energies the proton peak was sufficiently narrow to separate elastic scattering

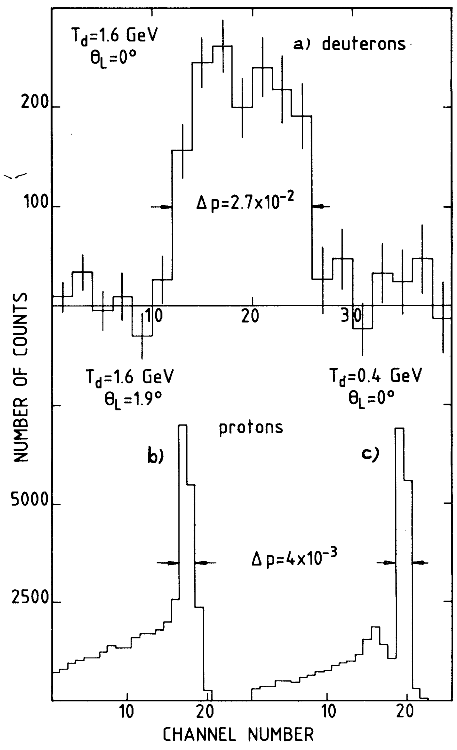

FIG. 1. Momentum spectrum of particles detected after target-empty subtraction: (a) scattered deuterons, (b) and (c) recoil protons.

TABLE I. Summary of T_{20} measurements in d-p scattering. Quoted errors are statistical only; scale uncertainty is discussed in the text.

T_d (GeV)	Particle detected	Laboratory angle (deg)	c.m. angle (deg)	T_{20}
0.3	p	2.1	175	-0.615 ± 0.035
0.4	p	0.0	180	-0.968 ± 0.038
0.5	p	2.1	175	-1.252 ± 0.048
0.6	p	0.0	180	-1.190 ± 0.030
0.7	p	2.1	175	-1.022 ± 0.044
0.8	p	0.0	180	-0.811 ± 0.031
0.8	p	2.2	175	-0.849 ± 0.040
1.0	d	0.0	180	-0.811 ± 0.121
1.1	p	1.9	175	-0.678 ± 0.048
1.2	d	0.0	180	-0.613 ± 0.134
1.3	p	1.9	175	-0.785 ± 0.033
1.4	p	1.5	176	-0.824 ± 0.067
1.4	d	0.0	180	-0.791 ± 0.143
1.5	p	1.9	175	-0.813 ± 0.037
1.5	p	3.5	170	-0.790 ± 0.038
1.6	p	1.9	175	-0.643 ± 0.040
1.6	d	0.0	180	-0.528 ± 0.248
1.6	d	6.0	175	-0.810 ± 0.304
1.7	p	1.9	175	-0.704 ± 0.048
2.0	p	2.2	174	-0.652 ± 0.063
2.3	p	3.4	170	-0.673 ± 0.244

TABLE II. Summary of A_y and A_{yy} measurements in d-p forwarding-angle scattering. Quoted errors are statistical only; scale uncertainty is discussed in the text.

T_d (GeV)	Laboratory angle (deg)	c.m. angle (deg)	A_y	A_{yy}
1.2	9.5	32.4	0.368 ± 0.011	0.772 ± 0.013
	10.5	35.8	0.288 ± 0.023	0.944 ± 0.026
	11.5	39.3	0.250 ± 0.019	0.980 ± 0.019
	12.3	42.1	0.144 ± 0.025	0.973 ± 0.026
1.6	7.6	25.9	0.350 ± 0.013	0.765 ± 0.014
	9.6	32.7	0.228 ± 0.020	0.917 ± 0.021
	11.6	39.7	-0.009 ± 0.020	0.130 ± 0.021

from scattering resulting in deuteron breakup, as shown in Fig. 1(c). This separation was not complete at higher beam energies [Fig. 1(b)] and therefore the proton elastic peak includes contributions from the inelastic part of the spectrum. We have, however, determined T_{20} for the inelastic part of the proton spectra and have found that it gives values that are the same as those for the elastic peaks at the same beam energy. Target-empty to target-full ratios were typically 10% for proton detection. The two detection modes gave consistent values of the c.m. cross section. As can be noticed from the complete results presented in Table I, data obtained at a given energy for different c.m. angles around 180° are equal within statistics so that the weighted mean only is plotted in Fig. 2. The values of T_{20} obtained by detecting protons (points) are seen to be in good agreement with the deuteron values (squares). As a further check, vector (A_y) and tensor (A_{yy}) analyzing powers[16] at c.m. forward angles were measured on SPES 4 at 1.2 and 1.6 GeV, for comparison with data taken at Argonne.[17] Our results, listed in Table II, are in good agreement in shape with those from Argonne, and the absolute normalizations agree within ±4% for A_y, but are 9% higher for A_{yy}. These differences are within uncertainties in analyzing powers of the reaction $d(d,p)t$ at 380 keV. The reasons for the discrepancy in $T_{20}(180°)$ are not understood, especially in light of the agreement at forward c.m. angles. The overall uncertainty in scale of T_{20} is estimated to be (10–15)%, mainly due to uncertainties in the analyzing power of the low-energy polarimeter. An independent limit on scale error is set by our value of $|T_{20}|$ at 0.5 GeV, which is 89% of the maximum possible value $|T_{20}|=\sqrt{2}$.

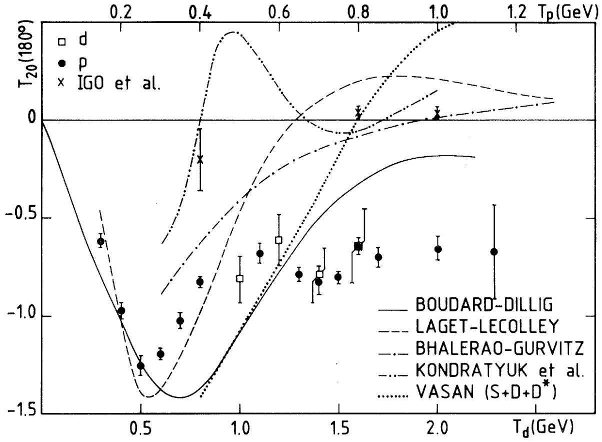

FIG. 2. $T_{20}(180°)$ in d-p elastic scattering as a function of incident deuteron energy (lower scale) or equivalent proton energy (upper scale). The dots and squares represent data obtained by detecting recoil protons and scattered deuterons, respectively. Theoretical calculations are described in the text.

The curves shown in Fig. 2 are various theoretical predictions of T_{20}, none of which adequately describes our results over the full energy range. For energies up to 1 GeV our data show the features expected from one-nucleon exchange (ONE)[6]: a descent to a lower bound of $T_{20} = -\sqrt{2}$. However, the width and position of this dip are only roughly reproduced by ONE. Addition of an N^* component to the deuteron wave function[6] shifts the ONE predictions above 0.8 GeV but does not improve the overall agreement with our data. The triangle graph model[3,7,8] in which one vertex is the reaction $pp \rightarrow d\pi$ successfully explains the bump of $\sigma(180°)$ around 1.3 GeV (T_d). Calculations[7,8] including ONE and $\Delta(1236)$ also account qualitatively for $T_{20}(180°)$ although they still rise too close to zero at the higher energies and give no evidence for the second dip around $T_d = 1.4$ GeV ($s^{1/2} = 3.25$ GeV) suggested by our data (see Fig. 2). Among various sources of improvement for the theory, proper relativistic treatment of deuteron spin[18] and rescattering effects[10-19] were shown to be important. Indeed, a more speculative attempt at improvement would result, for example, from the inclusion of dibaryons[20,21] or tribaryons in the intermediate states. One may notice that while a calculation[11] in which such tribaryons were introduced in order to fit the data of Ref. 5 is in disagreement with our data, it has been up to now the only available calculation producing above $T_d = 1$ GeV a structure in T_{20} somewhat similar to the one we have observed. However, a number of other theoretical sources of scattering have to be investigated before we can make conclusions about exotic effects.

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