Measurement of the Triple Scattering Parameter D_t in the Free n-p System at 170°*

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The triple scattering parameter D_t in the free $n-p$ system has been measured at a center-of-mass angle of 170°, using the 128-MeV polarized neutron beam at Harvard. The value found is -0.283 ± 0.209, which supports the strong negative value of the parameter predicted by the several phase-shift solutions of Breit *et al.* of Yale. This value, together with the values found by Patel *et al.* of this laboratory in 1962, discriminates sharply against solutions other than YLAN3M.

I. INTRODUCTION

IN 1962, P. M. Patel *et al.* carried out a measurement of the triple scattering parameter D_t in the free n-p system at five angles between 124° and 160°, using the 128-MeV polarized neutron beam at Harvard.[1] The several Yale semiphenomenological phase-shift predictions[2] for this parameter take on strong negative values at angles approaching 180°, but this negative tendency was not corroborated by the results of Ref. 1. This fact, together with the wide separation of the several phase-shift solutions near 180°, prompted us to undertake this measurement of the parameter at 170°.

The parameter D_t is defined[1,3] by

$$\langle\boldsymbol{\sigma}_t\rangle\cdot\mathbf{n}_3=\frac{(\mathbf{n}_2\cdot\mathbf{n}_3)}{1+P_2(\theta_2)\langle\boldsymbol{\sigma}_1\rangle\cdot\mathbf{n}_2}[P_2(\theta_2)+D_t(\theta_2)\langle\boldsymbol{\sigma}_1\rangle\cdot\mathbf{n}_2],$$

where $\langle\boldsymbol{\sigma}_1\rangle$ and $\langle\boldsymbol{\sigma}_t\rangle$ are the polarizations of the incident neutrons and recoiling protons, respectively, and $\mathbf{n}_2$ and $\mathbf{n}_3$ are the normals to the hydrogen scattering plane and the analyzer scattering plane, respectively. An experiment to measure D_t must have $\mathbf{n}_2$ and $\mathbf{n}_3$ parallel or antiparallel to one another.

II. APPARATUS AND PROCEDURES

A top view of the apparatus used for this measurement is shown in Fig. 1. The precession magnet enabled us to direct the incident polarization either upward or downward. By swinging the θ_2 arm, upon which the analyzer assembly was mounted, and which was pivoted directly beneath the liquid hydrogen target, $\mathbf{n}_2$ could be directed either upward or downward. The use of two θ_3 arms at equal angles to the analyzer centerline made possible the simultaneous collection of data for $\mathbf{n}_3$ up and down. An anticoincidence counter was installed on either side of the carbon analyzer to discriminate against random coincidence between protons traveling directly through C_1 and one of the back telescopes, and protons detected in C_2.

Use of the precession magnet enables us to form asymmetries such as

$$\epsilon_{LR}=(LR^+-LR^-)/(LR^++LR^-),$$

where LR^+ is the number of protons recoiling to the left from the hydrogen target and then scattered to the right by the carbon analyzer when the precession of the incident beam is 0°, and LR^- is this rate when the precession is 180°. This type of asymmetry has the virtue that the rates on either side of the minus sign are from the same set of counters, so the effects of differences in counter detection efficiency and of several misalignments are made negligible. By proper combination of the four asymmetries of this type we obtain

$$P_3P_1D_t=\tfrac{1}{4}\{[(\epsilon_{RR}+\epsilon_{LR})-(\epsilon_{LL}+\epsilon_{RL})]+P_2P_3[(\epsilon_{LL}+\epsilon_{LR})-(\epsilon_{RR}+\epsilon_{RL})]\}.$$

Since the value of P_1P_2 is well known from other measurements,[4] the combination

$$P_1P_2=\tfrac{1}{4}\{[(\epsilon_{LL}+\epsilon_{LR})-(\epsilon_{RR}+\epsilon_{RL})]+P_2P_3[(\epsilon_{RR}+\epsilon_{LR})-(\epsilon_{LL}+\epsilon_{RL})]\}$$

provides an important check on the asymmetries used in the evaluation of D_t.

The smallness of the lab angle (5°) forced us to adopt apparatus and procedures slightly different from those of Ref. 1 (see Fig. 2). Because of the high background rate expected, a larger hydrogen target, designed and built by Dr. Alan S. Carroll, was used to improve the ratio of the true rate to the background rate. To reduce random coincidence rates, solid angles were reduced by using smaller scintillators set at larger radii.

An additional problem arose due to proton contamination of the beam. About 1% of all the particles in the beam are protons. At large lab angles, because of the smallness of this percentage, they are not a problem, but at lab angles of 5° or less they are a problem because the θ_3 telescope nearest the beam axis is illuminated directly by them. With the precession magnet turned on, they are swept out of the

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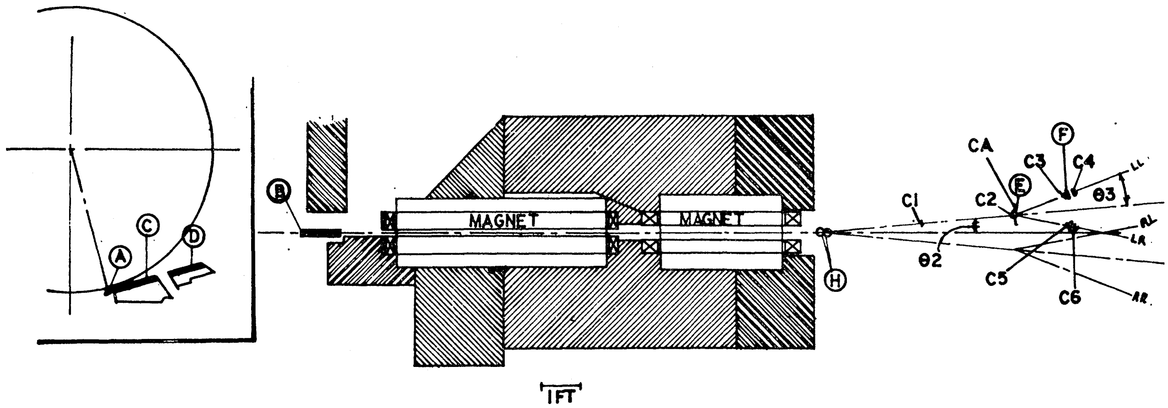

FIG. 1. Top view of experimental apparatus: A—beryllium, B—carbon polarizer, C—movable lead shield faced with tungsten, D—fixed lead shield, E—carbon analyzer, F—copper absorber, H—hydrogen target.

beam and not detected. Hence, the technique of Ref. 1, simply turning the magnet off to obtain 0° precession, was not satisfactory for us. Instead, we connected the upstream and downstream halves of the magnet to separate power supplies, and, leaving the field in the downstream magnet of fixed strength and polarity, we reversed the polarization by changing the polarity and strength of the field in the upstream magnet. For 180° precession, we had the fields parallel and of the same strength that was used in Ref. 1. For 0° precession, we had the fields antiparallel, and the strength of the upstream magnetic field adjusted to make the integral of the field strength over the whole length of the beam pipe equal to zero. The proper upstream magnetic field strength to make this integral zero was found by measuring the field intensity with a Hall Probe at closely spaced points along the axis of the beam pipe, and then integrating these measured values numerically. This measurement indicated that the vertical component of the polarization in this situation would be within $\pm 0.14\%$ of the expected value. By using the magnet in this fashion, backgrounds, measured with the target empty, were reduced to a uniformly acceptable value of about 15% of the rate with the target full.

III. RESULTS

The value which we found for D_t at 170° is -0.283 ± 0.209. This is the value obtained after compensating for backgrounds and random coincidences and applying corrections for the various systematic errors and uncertainties inherent in our geometry, apparatus, and techniques. These latter systematic corrections were small compared to the statistical uncertainty.

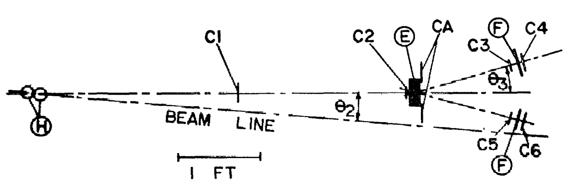

FIG. 2. Top view of target and counter geometry with θ_2(lab) = left 5°. H—hydrogen target; E—carbon analyzer; F—copper absorber; C1, C2, C3, C4, C5, and C6—coincidence counters; CA—anticoincidence counter.

TABLE I. χ^2 test of the several Yale phase-shift solutions by the six measured values of D_t.

Solution	χ^2	P
YLANO	61.00	$\ll 0.01$
YLAN1	32.74	$\ll 0.01$
YLAN2	80.57	$\ll 0.01$
YLAN2M	66.81	$\ll 0.01$
YLAN3	14.56	0.03
YLAN3M	6.73	0.37

The values of D_t measured in this experiment and Ref. 1, together with the several Yale phase shift predictions, are shown in Fig. 3. As can be seen from this graph, the strong negative value of the phase-shift solutions near 180° is supported by the 170° point. Also, as can be seen from the results of the "chi-squared" test summarized in Table I, the six measured

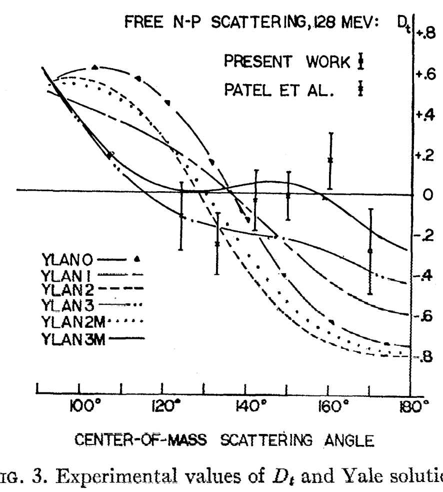

FIG. 3. Experimental values of D_t and Yale solutions.

values discriminate sharply against solutions other than YLAN3M.

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APPENDIX

It is perhaps worthwhile to point out why this measurement was made at 170° rather than 180°. For an ideal geometry of point targets and point detectors, the second scattering plane is undefined at $\theta_2=180°$, and experiments measuring the parameters D_t and R_t' become operationally indistinguishable. While such an experiment with an ideal geometry could be interpreted easily enough, it cannot be readily interpreted with finite angular resolutions such as ours. 170° was therefore chosen for being close enough to 180° to be significant in terms of the phase shift solutions, yet representing a lab angle large enough to define the second scattering plane satisfactorily.

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Differential Cross Sections for Triton-Induced Reactions on N^{14}

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Differential cross sections have been measured as functions of angle and bombarding energy in the region from 1 to 2 MeV for the following reactions: (1) $N^{14}(t,t)N^{14}$; (2) $N^{14}(t,\alpha)C^{13}$ going to the ground state and the 3.09-MeV state in C^{13}; (3) $N^{14}(t,d)N^{15}$ going to the ground state of N^{15}; and (4) $N^{14}(t,p)N^{16}$ going to the ground state and the 0.120-, 0.295-, and 0.392-MeV states of N^{16}. The total cross sections for the last three of these reactions at 2 MeV are: (2) 11 and 6 mb; (3) 48 mb; and (4) 7, 4, 9, and 8 mb, respectively. The energy and angular behavior of the differential cross sections suggest that most of these reactions proceed predominantly by direct interactions. The large absolute value of the cross section for the $N^{14}(t,d_0)N^{15}$ reaction, as well as the energy and angular behavior of the differential cross section, suggest that this reaction may proceed by a cluster exchange process. Distorted-wave Born approximation (DWBA) calculations provide satisfactory fits to the (t,α_0) angular distribution, but not the (t,d_0). Plane-wave calculations including exchange stripping give more acceptable fits to the (t,d_0) data.

I. INTRODUCTION

THE fact that the mass-3 particles (He^3 and H^3) have binding energies intermediate between that of the deuteron and of the α particle has led to the suggestion that the interactions of these particles with nuclei might emphasize certain characteristics of reaction mechansims not exhibited by the interactions of other particles.[1] This, in turn, might also reveal some aspects of nuclear structure which are not easily probed by other particles. The experimental study of low-energy mass-3 induced reactions has indeed suggested that a relationship exists between the mechanism of a reaction and the structure of the nuclei involved.[1–4] These investigations have further demonstrated that many of these reactions seem to proceed predominantly by direct interaction even at bombarding energies below 2 MeV.[4] The mass-3 induced reactions also appear to be particularly sensitive to the apparent cluster nature of the nuclei involved.[4,5] These two phenomena will be discussed in more detail below in connection with the results obtained in the current investigation.

This paper is a report of an experimental study of the interactions of tritons with N^{14}, and a semiquantitative explanation of the significant features observed. We have measured differential cross sections as functions of angle and bombarding energy in the range between 1 and 2 MeV, for the following reactions: (1) $N^{14}(t,t)N^{14}$; (2) $N^{14}(t,\alpha)C^{13}$ going to the ground state and the 3.09-MeV state in C^{13}; (3) $N^{14}(t,d)N^{15}$ going to the ground state of N^{15}; and (4) $N^{14}(t,p)N^{16}$ going to the ground state and the 0.120-, 0.295-, and 0.392-MeV states of N^{16}. Alpha-particle groups corresponding to the combined 3.68- and 3.85-MeV levels and to the 6.87-MeV

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