n-p Triple Scattering Parameters R and A*

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The parameters R and A have been measured for scattering of 140-Mev polarized protons by neutrons bound in deuterium (quasi-free p-n scattering). Corrections relating these results to the free n-p parameters have been applied, and the following values obtained:

θ_{cm}	R_{np}	A_{np}
42.1°	0.228±0.119	−0.037±0.094
52.5°	0.090±0.094	0.080+0.074
62.9°	−0.012±0.075	0.226±0.090
73.4°	−0.147±0.095	0.137±0.107
83.6°	−0.147±0.210	0.535±0.222

RATHER extensive experimental studies of proton-proton elastic scattering have been completed. Programs at 310,[1,2] 210,[3,4] and 140 Mev[5–7] have included measurements of the triple scattering parameters D,[1,4,5] R,[1,3,6] and A,[2,3,7] in addition to cross-section and polarization measurements.[8] Phase shift analyses[9,10] performed on these measurements indicate that the p-p scattering matrix has been very nearly determined.

Neutron-proton scattering has been less thoroughly studied. Cross-section and polarization measurements[8] are of lower accuracy, and no triple scattering measurements have been published.[11] As a result, conventional phase shift analyses find a continuum of solutions. (An analysis using data from a wide energy range, 13.7 to 350 Mev, rather than at one fixed energy, has found discrete solutions.[12] However, the n-p scattering matrix is far from being uniquely determined.) The measurements described below were undertaken to help remedy this situation.

We have measured the parameters R and A for scattering of 140-Mev polarized protons by neutrons bound in deuterium (quasi-free p-n scattering). The apparatus and method used were modifications of those used for the measurement of R for p-p scattering.[6] (For the measurement of A, the incident beam was passed through a bending magnet to orient its polarization along the direction of motion.) The liquid hydrogen target was replaced with a liquid deuterium target. A neutron counter detected the recoil neutron in coincidence with the scattered proton. Because of the internal momentum of the deuteron, the target neutron is not at rest, and the direction and energy of the recoil neutrons are not uniquely related to the direction of the scattered protons. Rather, the neutrons recoil over a range of angles, typically 15° full width at half maximum. The solid angle subtended by the neutron counter was such as to intercept about $\frac{1}{4}$ of the recoil neutrons, and its energy threshold was about 5 Mev. Our results are given as a function of laboratory angle of the scattered proton in Table I.

TABLE I. R and A for quasi-free p-n scattering.

θ_{lab}	R (quasi-free)	A (quasi-free)
20°	+0.029±0.080	+0.052±0.072
25°	−0.006±0.082	+0.123±0.059
30°	−0.061±0.063	+0.214±0.076
35°	−0.160±0.089	+0.098±0.095
40°	−0.164±0.207	+0.496±0.216

TABLE II. Laboratory scattering energy and center-of-mass scattering angle for equivalent free n-p events.

θ_{lab}	$\theta_{c.m.}$	$\Delta\theta_{c.m.}$	E (Mev)[a]	ΔE (Mev)
20°	42.1°	±3.6°	137.5	±7.5
25°	52.5°	±3.7°	137.5	±8.0
30°	62.9°	±3.7°	137.5	±8.5
35°	73.4°	±4.1°	137.5	±8.8
40°	83.6°	±4.4°	137.5	±9.1

[a] This energy refers to the R measurement; for A, the energy was 135.5 Mev.

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TABLE III. Corrections to the spectator model, ΔR and ΔA, and corrected values of R and A, for free n-p scattering.

$\theta_{c.m.}$	ΔR	R (free)	ΔA	A (free)
42.1°	+0.199±0.088	+0.228±0.119	−0.089±0.060	−0.037±0.094
52.5°	+0.096±0.046	+0.090±0.094	−0.043±0.045	+0.080±0.074
62.9°	+0.049±0.041	−0.012±0.075	+0.012±0.049	+0.226±0.090
73.4°	+0.013±0.034	−0.147±0.095	+0.039±0.050	+0.137±0.107
83.6°	+0.017±0.033	−0.147±0.210	+0.039±0.050	+0.535±0.222

The spectator model can be used to relate quasi-free p-n scattering to free n-p scattering. In this model one of the particles in the deuteron acts as "spectator," taking no part in the interaction and merely retaining the momentum it had before scattering (corresponding to an energy of a few Mev). The other particle is struck by the incident proton, and behaves as would a free particle with the same initial momentum. Using this model and our experimental geometry, we have calculated the laboratory scattering energy and center-of-mass scattering angle for equivalent free n-p events. These mean angles and energies, and their rms deviations, are given in Table II.

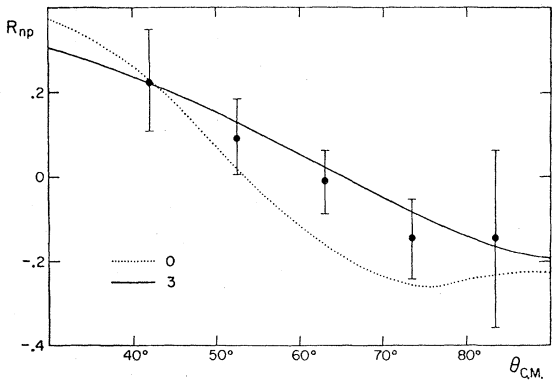

FIG. 1. R for free n-p scattering vs center-of-mass scattering angle. Also shown are the predictions of phase shift solutions of reference 12.

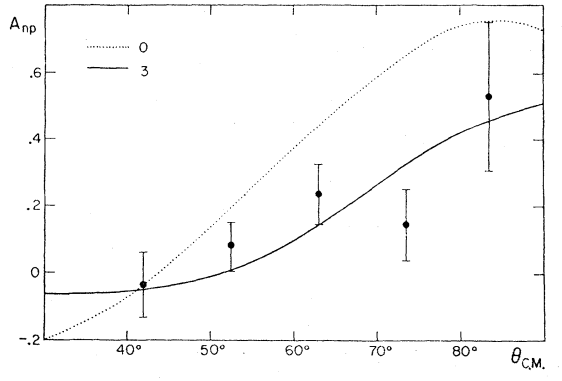

FIG. 2. A for free n-p scattering vs center-of-mass scattering angle. Also shown are the predictions of phase shift solutions of reference 12.

The spectator model neglects multiple scattering of the incident proton by the two target nucleons, final-state interactions between the two target nucleons, and the ambiguity as to which of the target particles was the struck particle, and which the spectator. Everett[13] has calculated corrections from the first two effects, and Cromer and Thorndike[14] have calculated corrections from the last two. The corrections of Cromer and Thorndike are given in Table III. The stated uncertainties allow for the neglected multiple scattering, as inferred from Everett's calculations, and for errors in averaging over the experimental resolution. The uncertainties in the corrections are comparable with the errors on the quasi-free measurements, and must be reduced before the accuracy of the experiment can be significantly improved.

The corrected values of R and A are listed in Table III, and plotted in Figs. 1 and 2. The uncertainty of the corrections has been combined quadratically with the error on the quasi-free measurement to give the error on the free measurement. Also shown in the figures are predictions of the phase shift solutions YLAN 0 and YLAN 3 of Hull, *et al.*[12] The other four solutions, YLAN 1, 2, 2M, and 3M, lie generally between the two curves shown. All solutions fit the R measurements adequately, but solutions 0, 2, and 2M fit the A measurements poorly. Solutions 3 and 3M provide the best over-all fit, and provide a very satisfactory representation of the data.

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