PHYSICAL REVIEW C VOLUME 21, NUMBER 3 MARCH 1980

Neutron-proton elastic scattering between 200 and 500 MeV. II. Measurement of R_t and A_t

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(Received 12 March 1979)

The Wolfenstein parameters R_t and A_t have been measured in free np elastic scattering at 220, 325, 425, and 495 MeV at 10° intervals in the center-of-mass range 60 to 160°, with errors typically ± 0.05.

[NUCLEAR REACTIONS $p(\vec{n},\vec{p})n, E = 220$, 325, 425, and 495 MeV, measured $R_t(\theta), A_t(\theta)$.]

I. INTRODUCTION

These measurements are part of a series[1-4] in progress at TRIUMF with the objective of determining the nucleon-nucleon interaction uniquely and accurately up to 500 MeV. A monoenergetic neutron beam of polarization $\langle\vec{\sigma}_n\rangle$ is scattered elastically from liquid hydrogen, and the polarization $\langle\vec{\sigma}_f\rangle$ of the proton in the final state is measured in a carbon polarimeter. The Wolfenstein parameters are defined[5] by

$$(1+P\langle\vec{\sigma}_n\rangle\cdot\vec{n})\langle\vec{\sigma}_f\rangle=(P+D_t\langle\vec{\sigma}_n\rangle\cdot\vec{n})\vec{n} + \langle\vec{\sigma}_n\rangle\cdot\vec{n}\times\vec{k}_i(R_t\vec{n}\times\vec{k}_f - R_t'\vec{k}_f) + \langle\vec{\sigma}_n\rangle\cdot\vec{k}_i(A_t\vec{n}\times\vec{k}_f - A_t'\vec{k}_f)\,, \quad (1)$$

where $\vec{k}_i$, $\vec{k}_f$ are unit vectors parallel to the lab momenta of incident neutron and scattered protons, and $\vec{n}$ is a unit vector parallel to $\vec{k}_f\times\vec{k}_i$. In the notation of Halzen and Thomas,[6] where the measured polarizations are ordered (incident, target; scattered, recoil),

$$R_t = K(s,0;\ 0,s)\,,$$

$$A_t = K(l,0;\ 0,s)\,,$$

where s and l stand for the transverse and longitudinal orientations.

II. EXPERIMENTAL DETAILS

The experimental layout is almost identical to that described previously[4] for measurements of P and D_t. The reader is referred to that paper, henceforth referred to as I, for close detail, and only the essentials are recapitulated here.

The polarized neutron beam is produced by charge exchange of the primary polarized proton beam from TRIUMF in a 20 cm liquid deuterium target. An almost monoenergetic neutron beam is achieved by selecting the full energy peak using time of flight with respect to the phase of the cyclotron rf. The vertical polarization $\langle\vec{\sigma}_p\rangle$ of the primary proton beam is rotated into the transverse horizontal direction $\vec{n}\times\vec{k}_i$ by a superconducting solenoid. The polarization of the neutron beam at production is then

$$\langle\vec{\sigma}_n\rangle=(r_t\vec{n}\times\vec{k}_f - r_t'\vec{k}_f)\langle\sigma_p\rangle + p\vec{n}\,, \quad (2)$$

where r_t and r_t' denote Wolfenstein parameters for interactions in deuterium. The small vertical component $p\vec{n}$ is of no interest here. The value of r_t is large (about -0.8) at the chosen production angle of 9° lab, and r_t' is small (<0.1), with the result that the polarization of interest is largely transverse, and about 60% in magnitude. For the present measurements, one precession magnet is used to precess this horizontal component in the horizontal plane to either the transverse or longitudinal direction. It also sweeps away charged particles; a veto counter completes the elimination of charged particles. The neutron beam, collimated to 7.5 cm diameter, then scatters from a 522 mm long liquid hydrogen target. Elastic scatters are selected by a coincidence between a polarimeter *PP* measuring the direction and polarization of recoil protons, and a 1.05 m^2 bank of scintillators detecting scattered neutrons with ~20% efficiency. The neutron detectors incorporate a veto of charged particles, and have a position sensitivity of ±3.5 cm horizontally and ±7.5 cm vertically. This position information, combined with the direction of the recoil proton in the polarimeter, selects *np* elastic scattering cleanly, and the inelastic background is <0.1%.

Values of R_t and A_t are derived from the vertical asymmetry in scattering of the recoil protons from carbon in the polarimeter. Instrumental bias is checked and eliminated by reversing the spin of the incident neutron beam periodically. This reversal is achieved by reversing the spin of the primary proton beam at the Lamb shift source.

The polarization and intensity of the primary proton beam are monitored by a polarimeter *MP* upstream of the deuterium production target. The horizontal component of polarization of the neutron beam is also monitored continuously by a polarimeter *MN* downstream of the liquid hydrogen target; for the measurements described here, this polarimeter is orientated in the vertical plane. An important function of this latter polarimeter is to check the precise orientation of the neutron polarization in the A_t configuration. It ought to be strictly longitudinal, but because of errors in setting up, it may be inclined at a small angle Φ towards the transverse direction. The measured parameters are then

$$\begin{aligned} R_t &= R_t \cos\Phi - A_t \sin\Phi \\ A_t &= A_t \cos\Phi + R_t \sin\Phi . \end{aligned} \tag{3}$$

The polarimeter *MN* measures the transverse component of polarization. The relative asymmetries in the A_t and R_t configurations therefore determine $\tan\Phi$. Values are given in Table I. Values of R_t and A_t given below are determined using Eqs. (3) and these values of Φ.

TABLE I. Values of Φ, defined by Eqs. (3), as a function of neutron beam energy.

Energy (MeV)	Φ (degrees)
220	0.60 ± 0.20
325	-3.59 ± 0.20
425	0.15 ± 0.20
495	0.38 ± 0.20

III. TREATMENT OF THE DATA

The asymmetries in the carbon polarimeter *PP* are determined using the first of the methods described in detail in I. The vertical and horizontal asymmetries in the R_t configuration are given by

$$\epsilon^v = A_c R_t \langle \sigma_n \rangle + \epsilon_0^v , \tag{4}$$

$$\epsilon^H = A_c P + \epsilon_0^H , \tag{5}$$

and for A_t by similar expressions. Here A_c is the analyzing power of carbon, which we have deter-

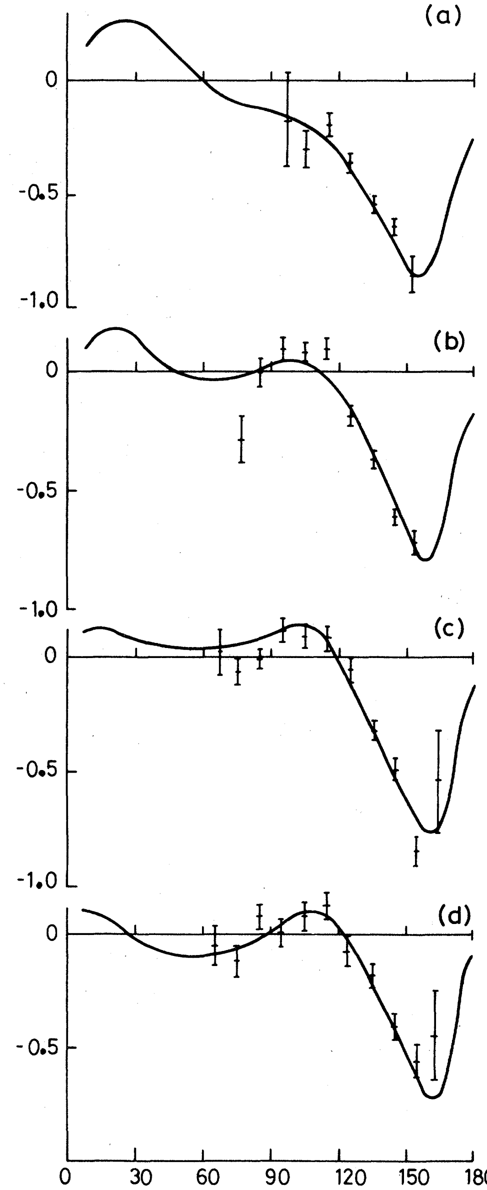

FIG. 1. Results for $R_t(\theta)$ (a) 220 MeV (b) 325 MeV (c) 425 MeV (d) 495 MeV fitted by phase shift analysis (Ref. 7).

TABLE II. Values of R_t and A_t.

Energy (MeV)	θ (degrees)	R_t	A_t
220 ± 1	97.56	−0.177 ± 0.207	−0.062 ± 0.265
	105.98	−0.301 ± 0.083	−0.013 ± 0.101
	115.90	−0.198 ± 0.050	0.138 ± 0.058
	124.90	−0.361 ± 0.039	−0.002 ± 0.043
	135.63	−0.546 ± 0.036	−0.163 ± 0.036
	144.36	−0.644 ± 0.032	−0.228 ± 0.033
	152.54	−0.855 ± 0.082	−0.127 ± 0.081
325 ± 1	76.85	−0.288 ± 0.097	0.059 ± 0.093
	85.31	−0.010 ± 0.054	0.271 ± 0.051
	95.23	0.093 ± 0.045	0.366 ± 0.043
	105.08	0.077 ± 0.039	0.332 ± 0.037
	114.53	0.090 ± 0.042	0.269 ± 0.042
	125.03	−0.188 ± 0.044	0.227 ± 0.044
	135.57	−0.370 ± 0.035	0.040 ± 0.035
	144.51	−0.611 ± 0.032	−0.062 ± 0.035
	153.50	−0.722 ± 0.049	−0.311 ± 0.053
425 ± 1	67.03	0.022 ± 0.096	−0.079 ± 0.110
	75.55	−0.062 ± 0.054	0.084 ± 0.057
	84.86	−0.009 ± 0.043	0.280 ± 0.045
	94.80	0.113 ± 0.046	0.335 ± 0.049
	105.06	0.085 ± 0.048	0.390 ± 0.050
	114.63	0.079 ± 0.049	0.320 ± 0.051
	124.96	−0.054 ± 0.050	0.257 ± 0.054
	135.44	−0.314 ± 0.042	0.078 ± 0.044
	144.50	−0.479 ± 0.043	0.012 ± 0.043
	153.84	−0.833 ± 0.062	−0.172 ± 0.060
	163.58	−0.527 ± 0.215	0.087 ± 0.250
495 ± 1	65.34	−0.049 ± 0.081	−0.026 ± 0.096
	75.43	−0.114 ± 0.062	0.047 ± 0.062
	84.78	−0.085 ± 0.051	0.156 ± 0.052
	94.67	0.011 ± 0.057	0.251 ± 0.059
	105.21	0.083 ± 0.060	0.354 ± 0.065
	114.71	0.133 ± 0.057	0.391 ± 0.063
	124.06	−0.070 ± 0.060	0.390 ± 0.068
	135.43	−0.168 ± 0.051	0.128 ± 0.056
	144.56	−0.403 ± 0.052	0.136 ± 0.055
	154.36	−0.552 ± 0.069	−0.032 ± 0.069
	162.93	−0.442 ± 0.191	0.309 ± 0.199

mined previously[2] with an absolute accuracy of ± 2%. The polarization $\langle\sigma_n\rangle$ of the neutron beam has been discussed at length in I. The quantities ϵ_0^v, ϵ_0^H are the instrumental asymmetries of the polarimeter. The value of ϵ_0^v is determined and eliminated by making half the measurements with $\langle\sigma_n\rangle$ reversed in sign; in practice, values are almost always zero within statistics. In our geometry, ϵ_0^H cannot be determined. However, if we take it to be zero like ϵ_0^v, values of P are in excellent agreement, within the statistical errors of ± 6%, with values measured in I. Since the latter are more accurate, and free from systematic bias, values of P from Eq. (5) will not be tabulated.

A target empty subtraction, typically 2% in magnitude, is made for events from the empty hydrogen target. With the target empty, measured values of R_t and A_t are compatible with zero. Since these parameters vary only slowly with energy, target empty data from the four energies of this experiment are averaged before the subtraction is made, so as to reduce statistical errors.

Raw data are binned into regions of ±5° in the center-of-mass scattering angle θ. The effect of the bin width is unfolded as follows. Suppose

$$R_t = R_0 + R_1(\theta - \theta_0) + R_2(\theta - \theta_0)^2 ,$$

where θ_0 is the value at the center of the bin. Then, averaging over the width of the bin,

$$\bar{R}_t = R_0 + R_2\langle(\theta - \theta_0)^2\rangle .$$

The coefficients R_2 are evaluated from the phase shift fit,[7] and used to determine R_0 from $\bar{R}_t$. In practice, the correction is never greater than 20%

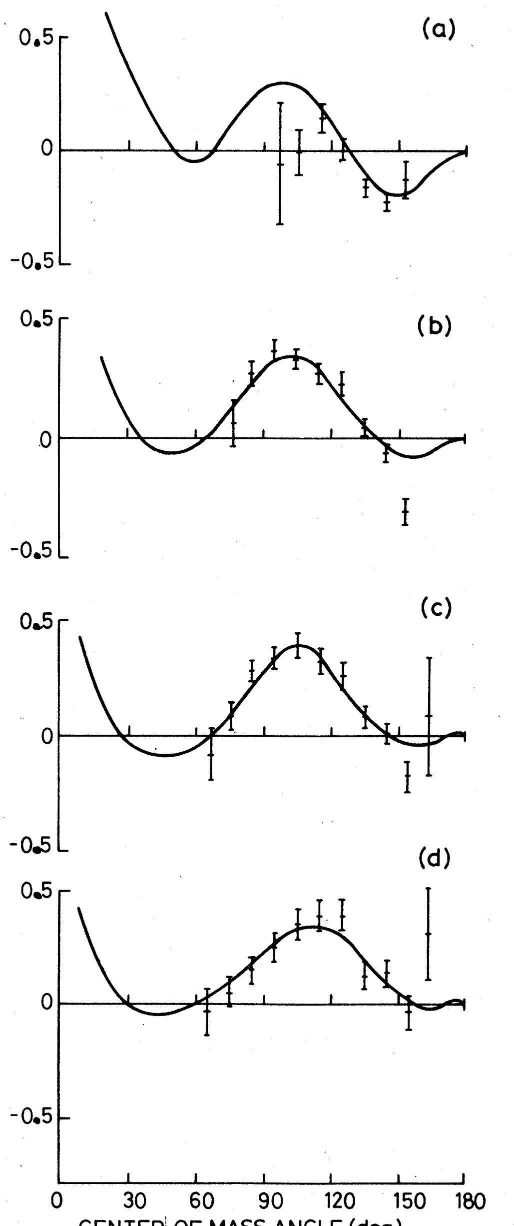

FIG. 2. Results for $A_t(\theta)$ (a) 220 MeV (b) 325 MeV (c) 425 MeV (d) 495 MeV fitted by phase shift analysis (Ref. 7).

of statistical errors. Values of A_t are treated likewise.

IV. RESULTS FOR R_t AND A_t

Results are given in Table II, and compared in Figs. 1 and 2, with the phase shift fits described in a following paper. They share a common normalization with P and D_t presented in I, and have an estimated normalization uncertainty of $\pm 3\%$. The measured asymmetries ϵ are determined absolutely, but the normalization of R_t and A_t is tied, through $\langle\sigma_n\rangle$, to the value of r_t for production of the neutron beam at 9° lab from deuterium, see Eq. (2). The value of $\langle\sigma_p\rangle$ in Eq. (2) is monitored with an absolute accuracy of $\pm 1.5\%$. As discussed in detail in I, r_t differs from the free *np* value R_t only by small and calculable amounts. The corresponding values of R_t at 9° lab are given in Table III. It is recommended that these values should be included in phase shift analyses. If the normalization of R_t and A_t in Table II is varied, values in Table III should vary in the opposite sense, so as to preserve the measured asymmetries, which depend on the product of the values given in the two tables.

The agreement of the phase shift fits with the measured points, shown in Figs. 1 and 2, is satisfactory. The χ^2 of the fit is slightly above 1 per point, because of a few isolated points with high values of χ^2. In particular, the value of A_t at 325 MeV, 153.5° has a $\chi^2 > 14$. If this point is omitted from the fits, the χ^2 of the remainder is 99.94 for 75 data points. It is not clear whether this slightly high value of χ^2 arises because our errors are slightly underestimated, or because of systematic errors in other data included in the phase shift fits.

V. VALUES OF r_t'

From values of Φ in Table I, giving the orientation of $\langle\vec{\sigma}_n\rangle$, it is in principle possible to work back to the ratio r_t'/r_t for production of the neutron beam at 9° lab, providing the spin precession along the path of the beam is known. Unfortunate-

TABLE III. Values of r_t and r_t' at 9° lab for $pd \to n$, derived from the properties of the neutron beam. The last two columns give corresponding values of R_t and R_t' after correction for final state interactions in deuterium.

Proton beam energy (MeV)	θ (degrees)	r_t	r_t'	R_t	R_t'
225.0	160.97	-0.840 ± 0.025	-0.008 ± 0.007	-0.790	-0.018
332.5	160.50	-0.853 ± 0.026	0.024 ± 0.008	-0.805	0.024
434.7	160.06	-0.809 ± 0.024	0.051 ± 0.008	-0.757	0.063
506.4	159.76	-0.725 ± 0.021	0.058 ± 0.008	-0.664	0.076

ly, the neutron beam emerges through the fringe field of a dipole magnet, used to steer the primary proton beam to the beam dump. This magnet is extremely inaccessible and its field is not known with sufficient precision. Nonetheless, the energy dependence of r_t'/r_t may be correlated with the measured values of Φ:

$$\tan^{-1}(r_t'/r_t) = (C_1 I_1 + C_2 I_2)/v - \Phi \, ,$$

where $I_{1,2}$ are currents in magnet 1 and the precession magnet; C_2 is accurately known (±1%), and v is the lab velocity of the neutron beam. Phase shift solutions at the four energies give predictions for R_t and R_t', the free *np* values. They may be corrected for final state interactions in deuterium, using the methods developed by Cromer[8] and by Reay *et al.*[9] Their formulas are generalized to relativistic form, and to the full range of Wolfenstein transfer parameters in the Appendix. Using these to deduce r_t/r_t', one deduces values of C_1. If one now takes the weighted mean value of C_1, one can reverse this procedure to improve the determination of r_t', hence R_t', as a function of energy. In practice, the value of C_1 is dominated by the phase shift solution at 210 MeV, and values of r_t' and R_t' at other energies may be regarded as derived from Φ. In particular, the value of R_t' at 495 MeV is a useful constraint in the phase shift analysis. Details are given in Table III.

VI. SUMMARY AND CONCLUSIONS

Accurate values of R_t and A_t for free *np* elastic scattering have been measured over a wide angular range from 220 to 495 MeV. The values change only slowly with energy. Values of R_t' at the angle of production of the neutron beam are also inferred. These new results play a major role in fixing phase shifts uniquely and accurately up to 500 MeV. The data are statistically in satisfactory agreement with the phase shift solutions.

ACKNOWLEDGMENTS

We are grateful to Professor J. Sample and the staff of TRIUMF for their assistance and efforts in this experiment. We are particularly grateful to Dr. J. Beveridge, Dr. P. Schmor, and Mr. M. MacDonald for their work in producing a reliable polarized beam of high intensity, and to Mr. G. Waters for his assistance with the chambers and electronics. N. W. thanks the Science Research Council for a studentship. R. K. and R. D. thank the Natural Sciences and Engineering Research Council of Canada for financial support.

APPENDIX

Here we give relativistic expressions needed to evaluate Wolfenstein transfer parameters for charge exchange scattering from deuterium. The notation is that of Hoshizaki[5] and Reay *et al.*[9] The latter authors show that the parameters are given by expressions of the form

$$I_0 R_t(t) = a(t) I_0^{np} R_t^{np} + 2b(t) I_0^{ces} R_t^{ces} \, .$$

The term $I_0^{np} R_t^{np}$ refers to free *np* scattering, and the form factor $a(t)$ dominates at large momentum transfer t. The second term corrects for final state interactions where the recoil proton and spectator proton are in a $^1S_0$ state; $b(t)$ dominates as $t \to 0$.

The scattering matrix for free incident proton 1 on a free neutron 2 is written

$$M^{np}(1,2) = A + B\sigma_{1n}\sigma_{2n} + C(\sigma_{1n} + \sigma_{2n}) + E\sigma_{1q}\sigma_{2q} + F\sigma_{1p}\sigma_{2p} \, .$$

Charge exchange from a deuteron, leaving protons 1 and 3 in the $^1S_0$ final state is deduced using singlet and triplet projection operators Λ^s and Λ^t, with the result (after summing over the spin of spectator particle 3)

$$M^{ces} = \mathrm{Tr}_3[\Lambda^s(1,3) M^{np}(1,2) \Lambda^t(2,3)] = \tfrac{1}{2}[\alpha - \beta\sigma_{1n}\sigma_{2n} - \gamma\sigma_{1p}\sigma_{2p} - \delta\sigma_{1q}\sigma_{2q} + \tfrac{1}{2}C(\sigma_{1n} + \sigma_{2n}) + \tfrac{1}{2}iC(\sigma_{1q}\sigma_{2P} - \sigma_{1P}\sigma_{2q})] \, ,$$

where

$$4\alpha = 3A - B - E - F \, ,$$

$$4\beta = A - 3B + E + F \, ,$$

$$4\gamma = A + B + E - 3F \, ,$$

and

$$4\delta = A + B - 3E + F \, .$$

Then

$$3I_0^{ces} = |\alpha|^2 + |\beta|^2 + |\gamma|^2 + |\delta|^2 + |C|^2 \, ,$$

$$R_t^{ces} = X\cos(\theta' - \theta_L') + Y\cos\theta_L' + K_{qp}\sin(\theta' - \theta_L') \, ,$$

$$R_t'^{ces} = X\sin(\theta' - \theta_L') - Y\sin\theta_L' - K_{qp}\cos(\theta' - \theta_L') \, ,$$

$$A_t^{ces} = X\sin(\theta' - \theta_L') + Y\sin\theta_L' - K_{qp}\cos(\theta' - \theta_L') \, ,$$

and

$$A_t'^{ces} = -X\cos(\theta' - \theta_L') + Y\cos\theta_L' - K_{qp}\sin(\theta' - \theta_L') \, ,$$

where

$$3I_0 X = |C|^2 - \tfrac{1}{4}|A + B - E - F|^2 \, ,$$

$$3I_0 Y = \mathrm{Re}\{(A - B)^*(F - E)\} \, ,$$

$$I_0 K_{qp} = \mathrm{Re}\{ic(A + B - E - F)^*\} \, ,$$

$$\theta' = \pi - \theta \, ,$$

and θ_L' is the lab angle of the emerging neutron 2.

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