PHYSICAL REVIEW C VOLUME 25, NUMBER 4 APRIL 1982

Spin transfer measurements for $pp \to pp$ at 800 MeV

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(Received 9 November 1981)

The spin depolarization parameters D_{NN}, D_{SS}, D_{LS}, and the spin transfer parameters K_{NN}, K_{SS}, K_{LS} have been measured for $pp \to pp$ at 800 MeV. Angular range is 21 to 90° c.m. for the D parameters, and 46 to 90° c.m. for the K parameters. Typical uncertainties are about ± 0.025. These data, when combined with previous data make possible a complete isovector phase shift and amplitude analysis at 800 MeV.

[NUCLEAR REACTIONS ^{1}H$(p,p)^1$H, $E=800$ MeV, measured D_{NN}, D_{SS}, D_{LS}, K_{NN}, K_{SS}, K_{LS}, $\theta=21$ to 90° c.m.]

I. INTRODUCTION

A complete determination of the pp elastic phase shifts and amplitudes at 800 MeV is important for several reasons. Recently much interest has been generated by the energy dependent structure observed near this energy. Interpretations range from exotic dibaryon resonances[1,2] to threshold effects within conventional models.[3–5] It is generally agreed, however, that a definitive interpretation will not be possible without a complete set of measurements at least at several nearby energies.

Further interest in the nucleon-nucleon amplitudes comes from nuclear physics, in which the amplitudes are essential for microscopic models. 800 MeV is the highest and most common energy at the Clinton P. Anderson Meson Physics Facility (LAMPF), and is the energy at which precise NN amplitudes are most urgently required.[6,7]

Determination of the amplitudes at 800 MeV is considerably more difficult than at lower energies (near or below the inelastic thresholds) where unitarity allows simplifying assumptions. Five complex amplitudes are required, so at least nine spin-dependent experiments are needed to determine five magnitudes and four phases.

The present measurements of D_{NN}, D_{SS}, D_{LS}, K_{NN}, K_{SS}, and K_{LS} provide six such parameters. [Note that identity of particles requires that $D(\theta)=K(\pi-\theta)$, so that the data may be plotted as three parameters from 0 to 180° c.m. in Figs. 1 to 3.] When combined with previous measurements of cross section,[8] analyzing power,[9–13] and the spin correlation parameters A_{NN} (Refs. 14,15) and A_{LL} (Ref. 16) these bring the total number of parameters to 10. These make it possible for the first time to completely determine the pp (isovector) phase shifts and amplitudes[17] at 800 MeV.

Further pp data is still required, however, to improve the accuracy of the solutions. Preliminary data exists for D_{LL} and D_{SL},[18] and work is proceed-

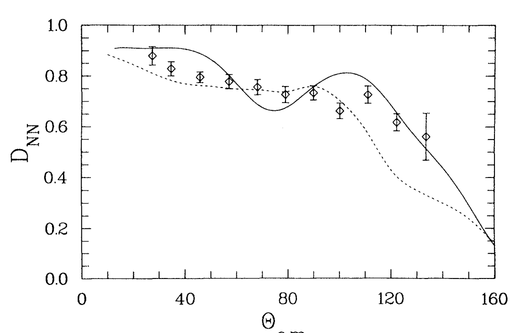

FIG. 1. D_{NN} for $pp \to pp$ at 800 MeV, compared with Arndt's solutions (SF81 solid line, CD79 dashed).

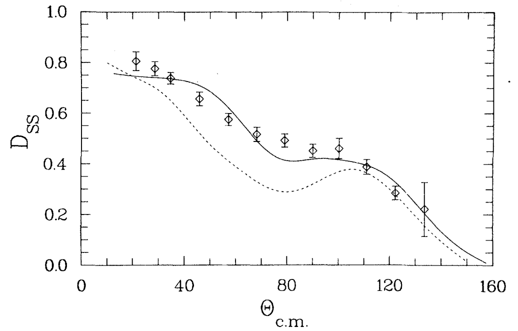

FIG. 2. D_{SS} for $pp \rightarrow pp$ at 800 MeV, compared with Arndt's solutions (SF81 solid line, CD79 dashed).

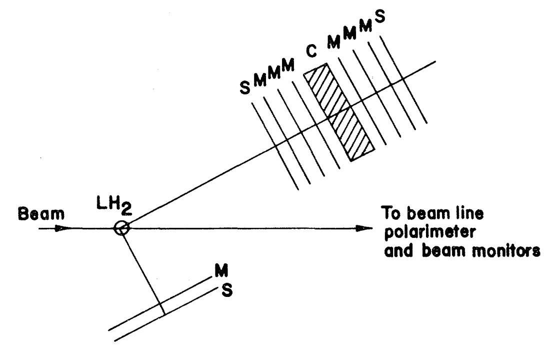

FIG. 4. Sketch of the apparatus. S denotes scintillators, M denotes multiwire drift chambers, and C the carbon block.

ing in the measurements of K_{LL}, K_{SL},[19] A_{SS}, and A_{SL}.[20]

II. EXPERIMENTAL METHOD

Measurement of the spin depolarization and transfer parameters consists in principle of scattering a beam of polarized protons from an unpolarized target and measuring the final state polarization. The notation is defined in Ref. 21. For both scattered and recoil particles (D and K parameters, respectively), the sign is defined as plus for spins up (N), left (S) and parallel to momentum (L) for both initial and final states and for protons scattered left. In the older Wolfenstein notation, the parameters D_{NN}, D_{SS}, D_{LS}, K_{NN}, K_{SS}, and K_{LS} are known as D, R, A, D_t, R_t, and A_t, respectively.

The experimental setup is illustrated in Fig. 4. The LAMPF polarized proton beam ($P_b \simeq 0.8$) was focused (few mm diameter) onto a 2.5 cm thick liquid hydrogen target. N, S, and L beam spin directions were obtained by an innovative spin processor.[22] Elastically scattered protons were distinguished from background by detecting both scattered and recoil protons in multiwire drift chambers (MWDC) and requiring the precise angular correlation distinctive of two body final states. Background was less than one quarter of one percent and was neglected.

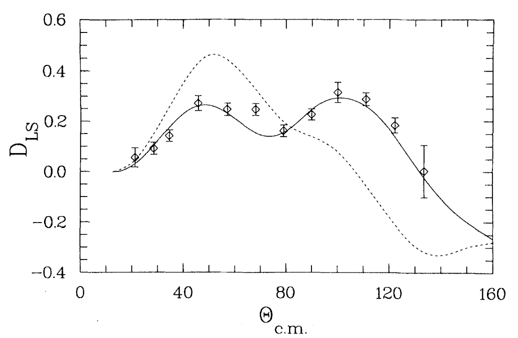

FIG. 3. D_{LS} for $pp \rightarrow pp$ at 800 MeV, compared with Arndt's solutions (SF81 solid line, CD79 dashed).

The spin of one final state proton was analyzed in a carbon polarimeter, which is described in detail in Ref. 23. Similar devices have been used for similar measurements at TRIUMF,[24] SIN,[25] and the LAMPF HRS.[26] Charged particle trajectories both before and after scattering from carbon were each determined by a scintillator and three X-Y pairs of drift chambers (Fig. 4). A good event was required to have good (10 ns) time of flight, to scatter in the hydrogen and carbon targets, and to have a single consistent trajectory (± 1 mm in each set of three drift chambers, <5 mm closest approach between front and back trajectories). The minimum acceptable scattering angle in carbon ranged from 2.9° for pp scattering forward of 40° laboratory to 4.6° at backward pp angles where the influence of the multiple Coulomb scattering tail was more serious.

The L-R and D-U asymmetries (e_{LR}, e_{UD}) were extracted from the azimuthal distribution using well-known techniques.[27] In order to reduce instrumental asymmetries, events with polar and azimuthal angles θ, ϕ were rejected if the conjugate trajectory θ, $\phi+\pi$ would not also have been accepted. Instrumental asymmetries were about 0.005,[23] and cancel to first order (see below).

The polarization P_2 of the protons scattered from hydrogen are given by $P_2 = e/A_C$, where the (inclusive) carbon analyzing power A_C is calculated from an energy dependent fit[28] to data from TRIUMF,[24] SIN,[25] and LAMPF.[23,26,29] The good agreement indicates that instrumental asymmetries are indeed small. The 2.5% uncertainty in A_C (Ref. 28) is included in the data of Table I as a point-to-point uncertainty.

The spin transfer parameters D_{NN} or K_{NN} are given by

$$\vec{P}_2 \cdot \hat{n} = \frac{e_{LR}}{A_C} = \frac{A_p + D_{NN}(\vec{P}_b \cdot \hat{n})}{1 + A_p(\vec{P}_b \cdot \hat{n})} , \quad (1)$$

where $\hat{n}$ is the unit vector normal to the scattering plane, P_b is the beam polarization, and A_p is the analyzing power for $pp \to pp$ (obtained from Refs. 9 and 10). For D_{SS} and K_{SS}, the equation simplifies to

$$\vec{P}_2 \cdot \hat{s} = \frac{e_{DU}}{A_C} = D(\vec{P}_b \cdot \hat{s}) \quad (2)$$

and similarly for D_{LS}, K_{LS}.

The beam polarization was measured using the beam line polarimeters.[30] For N and S spins, the polarization was measured in the same beam line (*EPB*) as the main experiment. For L beam spin, the polarization was measured in the adjacent (*LB*) beam line. A $(4 \pm 2)\%$ correction was made for the difference in polarization between these two lines (which was measured before and after the L-spin runs). Undesirable beam spin components were monitored by a combination of the *EP* and *LB* polarimeters, and an uncertainty of ± 0.005 has been added where appropriate.

During the measurements, the beam polarization was reversed at the ion source every minute. This has the effect of changing the sign of P_b in Eqs. (1) and (2). Subtracting the two equations with opposite sign of P_b gives a first order cancellation of instrumental asymmetries.

In the case of Eq. (1), there are several ways of extracting D_{NN} from the two equations with $\pm P_b$. The two equations may be subtracted as mentioned above, each equation may be solved separately, or the two equations may be solved simultaneously to eliminate A_C. All three methods gave consistent results. Final data were obtained from the first method.

The carbon analyzing power A_C was extracted from all data runs [e.g., solving the two equations 1 (with $\pm P_b$) to eliminate D] and included in the global fit.[28] Results were consistent with data from other laboratories,[24,25] the LAMPF HRS carbon polarimeter,[26] and data with the present polarimeter[23] in the direct beam.[28]

Carbon thickness ranged from 3 to 25 cm depending on the scattering angle from hydrogen. At several angles, data were taken with two carbon thicknesses; results were consistent. The thicknesses used as a function of energy are given in Refs. 23 and 28.

At several angles, measurements were made with the polarimeter both to the left and right of the beam, in order to check instrumental asymmetries. No significant differences were observed.

A correction was included for the finite azimuthal acceptance of the pp scattering. Since $\hat{n}$ and $\hat{s}$

TABLE I. Spin depolarization and transfer parameters D_{NN}, D_{SS}, D_{LS}, K_{NN}, K_{SS}, K_{LS}, for $pp \to pp$ at 800 MeV.

θ_{lab}	$\theta_{c.m.}$	D_{NN}	ΔD_{NN}	D_{SS}	ΔD_{SS}	D_{LS}	ΔD_{LS}
8.9	21.2			0.806	0.037	0.056	0.038
11.5	27.3	0.880	0.036				
12.0	28.5			0.776	0.028	0.092	0.024
14.6	34.6	0.829	0.028	0.738	0.023	0.143	0.023
19.5	45.8	0.796	0.021	0.657	0.027	0.272	0.030
24.5	57.1	0.779	0.028	0.576	0.024	0.248	0.025
29.5	68.1	0.757	0.030	0.518	0.028	0.248	0.024
34.6	79.0	0.728	0.032	0.493	0.026	0.163	0.023
39.9	89.9	0.735	0.028	0.452	0.026	0.227	0.022
		K_{NN}	ΔK_{NN}	K_{SS}	ΔK_{SS}	K_{LS}	ΔK_{LS}
45.0	79.9	0.664	0.031	0.462	0.040	0.315	0.040
50.6	69.0	0.728	0.034	0.389	0.029	0.288	0.026
56.6	57.8	0.619	0.034	0.285	0.027	0.184	0.030
62.9	46.4	0.562	0.093	0.221	0.107	0.002	0.104

[Eqs. (1) and (2)] are defined relative to the scattering plane, this involves replacing P_b with $P_b\langle\cos\phi_H\rangle$, where ϕ_H is the angle between the horizontal and the plane of the first scattering. The maximum value of this correction (at the most forward angle) was 2%.

In general, the data are averaged over the full angular acceptance of the polarimeter (about $\pm 3^\circ$ laboratory). For D_{SS} and D_{LS}, the most forward angle setting has been binned to give a 21° c.m. point from the most forward third and a 28° c.m. point from the remainder. The D_{NN} data were not binned in this way since these, which were the earliest taken, were subject to an instrumental asymmetry that cancels over the full acceptance, but may become significant for a bin at one edge of the polarimeter. This asymmetry is associated with the fast clear system[23] (designed to reject events that did not scatter significantly in the carbon) and affects only the earliest data, and only the smallest carbon scattering angles ($<4^\circ$). We have measured and included this correction, and find that its effect on the data quoted here and in Ref. 28 is negligible (<0.001). The angle quoted is the average angle of the events in the bin, with an uncertainty of about $\pm 0.1^\circ$ laboratory.

The primary method of absolute polarization calibration at LAMPF is the ion source quench ratio.[10,11,31] However, the measurements described here and in Ref. 28 are (to first order) an independent absolute calibration. For example, in one experiment (Refs. 9 and 10) we measured an asymmetry $e_1 = A_p P_b$; experiment 2 (Refs. 28 and 29) measures $e_2 = A_C P_b$; experiment 3, the double scattering with L or S beam spin described here and in Ref. 28, measures $e_3 = A_C A_p$. In principle, we can solve these three equations for P_b, A_p, and A_C independently of the quench ratio. The energy change between A_C in the second and third equations complicates this, but the many energies and small energy dependence above 500 MeV mean that the good agreement reported in Ref. 28 constitutes a partial independent check of the absolute calibration.

Briefly, the normalization of A_C is derived via the energy dependent fit[28] from a combination of the absolute measurement discussed above, the quench calibrations,[10,11] and SIN (Ref. 27) and TRIUMF (Ref. 24) calibrations. This normalization uncertainty ($\pm 2.5\%$) has been included in the data of Table I as a point-to-point uncertainty. The normalization uncertainty for the beam polarization is estimated[10] to be $\pm 1\%$ and should be applied equally to all data in this paper, and to all polarization data from LAMPF (e.g., Refs. 9, 10, and 11).

III. CONCLUSIONS

The data are listed in Table I and plotted in Figs. 1 to 3 in comparison with Arndt's phase shift solution[32] (SF81 solid line). The preliminary values of the data reported previously[33] are included in this fit. Also shown are results from a preexisting solution (CD79, dashed line). The impact of the preliminary data on the preexisting solution (CD79) was dramatic. The present phase shift predictions are reasonable, though the smaller uncertainties on the present data make it apparent that the predictions exhibit more structure than is observed in the data.

IV. ACKNOWLEDGMENTS

We would like to thank Harvey Willard for his cooperation and for the loan of the Case Western Reserve University trailer and computer, members of the BASQUE, SIN, and LAMPF HRS groups for sharing their knowledge with us, Hal Spinka for his help during data taking, and Kok-Heong McNaughton for help in writing software and analyzing data. Phil Bevington, who died on August 19, 1980, was the original spokesman of this experiment. This work was supported in part by the U. S. Department of Energy.

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