LA--9504-T

DE83 000462

Measurement of the Spin-Spin Correlation Parameter $C_{LL}(\theta)$ in Proton-Proton Scattering

Sidney Jay Stuart*

*Physics Department, New Mexico State University, Las Cruces, NM 88003.

Los Alamos Los Alamos National Laboratory
Los Alamos, New Mexico 87545

C O N T E N T S

ABSTRACT.....	1
1. INTRODUCTION.....	2
2. EXPERIMENTAL SETUP.....	7
3. DATA REDUCTION.....	21
4. RESULTS.....	41
5. SUMMARY AND CONCLUSIONS.....	50
6. ACKNOWLEDGMENTS.....	51
7. REFERENCES.....	52

LIST OF TABLES

I. BINNED C_{LL} OVER THIRTEEN ENERGIES.....	42
II. FITTED C_{LL} VALUES.....	49

LIST OF FIGURES

1.	Diagram of LAMPF beam switchyard showing experimental area "B".....	9
2.	Diagram of experimental setup.....	10
3.	Schematic of beam electronics.....	13
4.	Schematic of C_{LL} electronics.....	15
5.	Histogram of $\Delta\Phi$	23
6.	Histogram of calculated beam energy showing output of PEKFIT.....	24
7.	Histogram of DCA.....	30
8.	Histogram of X axis values of collision positions.....	32
9.	Histogram of Y axis values of collision positions.....	33
10.	Histogram of Z axis values of collision positions.....	34
11.	Histogram of $(\theta_R + \theta_L)_{cm}$	35
12.	Histogram of $\Delta\Phi_b$ peaks.....	36
13.	Histogram of Y2 values	40
14.	Plotted values of C_{LL}	44-46
15.	Plotted values of A from the fit $C_{LL}(\theta) = A + B \cos^2(\theta)$	47
16.	Plotted values of B from the fit $C_{LL}(\theta) = A + B \cos^2(\theta)$	48

MEASUREMENT OF THE SPIN-SPIN CORRELATION PARAMETER $C_{LL}(\theta)$
IN PROTON-PROTON SCATTERING

BY

SIDNEY JAY STUART

ABSTRACT

The experimental procedures and methods of data analysis used to measure the spin-spin correlation parameter $C_{LL}(\theta)$ in proton-proton scattering at thirteen different energies in the range 300 to 800 MeV are presented. The results compare favorably with previous data. Good agreement is found with phase shift predictions at energies below 500 MeV.

INTRODUCTION

Everything we perceive is the direct result of a physical interaction. It is therefore reasonable that we should be interested in these phenomena. After much study physicists have been able to classify the observed interactions into four fundamental types: gravitational, Coulomb, weak and strong. The gravitational and Coulomb interactions are familiar to everyone, as their results can be easily seen and felt. Weak and strong interactions, on the other hand, have only been known for the last 70 or 80 years at most. This is because they both have a very short range ($< 10^{-12}\text{cm}$) and only became evident when the atomic nucleus and its components were studied. Much progress has been made in understanding the weak interaction, but a lot about the strong interaction is still unknown because of its complex behavior.

The strong nuclear force is an interaction found between particles called hadrons (nucleons, hyperons, mesons, etc.). In the variety of possible interactions between hadrons, perhaps the most interesting are those between nucleons. This is so because nuclei consist of interacting nucleons and form the basis of our world. Some properties of the nucleon-nucleon interaction are given by Paul [PA-69] as:

- 1) An attractive well of range about $2 \times 10^{-13}\text{cm}$ and depth 30-50 MeV/nucleon combined with a repulsive core of range about $0.4 \times 10^{-13}\text{cm}$ and magnitude at least 300 MeV.

2) It is charge symmetric, i.e. n-n bonds = p-p bonds and also charge independent, n-n bonds = n-p bonds = p-p bonds.

3) It contains exchange components as well as non-exchange components. Spatial as well as spin symmetry control the exchange parts.

4) There is a non-central tensor component of the force.

5) There is a velocity dependent spin orbit interaction.

This is obviously a very involved interaction. To study something this complex it is generally useful to observe the simplest cases. The two-nucleon systems are a good place to start.

The possible systems having two nucleons are n-n, n-p and p-p. Of the three, only one, n-p (the deuteron), is found as a bound state. The deuteron has been studied extensively. It was information found from studying the deuteron that showed the nuclear force to be spin dependent. Only a limited amount of information can be gleaned from a single bound state system with no bound excited state, however; if more is needed, one must have recourse to scattering experiments.

Using scattering experiments to delve into the strong force is complicated by the interaction's spin dependence. This means that the scattering cross section is dependent on the spin orientation of the particles in an interaction. In the coordinate system defined by the beam line and scattering plane of an experiment, there can be three different orientations for the spin of each particle. The possible

alignments are parallel to the beam, perpendicular to the scattering plane (and the beam), or perpendicular to the beam line in the the scattering plane. According to Wilson [WI-63], the spin state of the two particles is determined by 16 independent matrices containing 256 scalar coefficients. Since it would take 256 different experiments at each energy and angle to measure these coefficients, one would like to simplify the problem if possible. One means of simplification is to assume parity is conserved and that the N-N interaction is invariant under time reversal. These two assumptions simplify the problem immensely. If one limits the experiments to those between particles that have the same charge (p-p or n-n), then the quantities that need to be found are reduced to ten.

From the experimentalists' point of view, there are a myriad of possible experiments to obtain these values, given that there are three possible values of spin and four places to measure the spin (beam, target, scattered and recoil proton). Some of these are redundant though, for the same reasons given above to simplify the theoretical calculations. Still there are many more possible experiments than ten, thus giving the experimenter a choice. This choice allows him to pick tests of the N-N interaction that are possible to perform with the available tools and that will return useful results in a reasonable time. Once the values are found experimentally, mathematical formalism is used to relate the experimental values to the theoretical representations. These

representations can be in many forms, such as helicity amplitudes or partial wave expansions [Y0-80].

Over ten years ago, when polarized proton beams first became available, a decision was made at the Argonne National Laboratory to measure the difference in the total cross section $\Delta\sigma_L$ for parallel and antiparallel longitudinal spin states in proton-proton scattering. It was seen at that time that another p-p scattering parameter $C_{LL}(\theta)$ could be measured concurrently, getting two numbers for the price of one [AU-78]. Due to some problems with the measurement of the beam polarization at the ZGS, as well as controversy over the results [BU-81], the experiments were repeated at the Los Alamos Meson Physics facility. They were done over a smaller energy range but with smaller energy intervals. The rest of this paper discusses the measurement of $C_{LL}(\theta)$ carried out at that time, and the data reduction.

The spin-spin correlation parameter $C_{LL}(\theta)$ is one measure of the spin and angular dependence of the nuclear interaction in elastic scattering. The values are often measured around 90° in the center-of-momentum frame because it is at that point the formalism becomes simplified. This quantity is defined in experimental terms as

$$C_{LL}(\theta) = \frac{1}{P_B P_T} \frac{(I^{++} + I^{--}) - (I^{+-} + I^{-+})}{(I^{++} + I^{--}) + (I^{+-} + I^{-+})},$$

where θ is in the center-of-momentum reference frame, P_B and P_T are

the polarizations of the beam and target, respectively, and $I^{\pm\pm}$ are the scattered intensities for a particular beam and target spin direction. The scattered intensity is defined as the number of particles scattered over some period of time, normalized by the number of beam particles that go through the target during that time. The + stands for polarization in the direction of the beam, while - is in the opposite direction. The first sign is for the beam and the second for the target. The formalism behind the definition of $C_{LL}(\theta)$ is complex and may be found in the literature [YO-80]. Its measurement is not as difficult to understand though and is described below.

EXPERIMENTAL SETUP

The experimental data used to find $C_{LL}(\theta)$ were taken at the Los Alamos Meson Physics Facility (LAMPF). A polarized proton beam with a kinetic energy range of 300 to 800 MeV was provided. This beam starts in a Lamb-shift polarized ion source [LA-69, OH-71]. The ion source has been documented very well, so only a brief discussion of its important features will be given here. For this experiment, 500 eV protons pass through a cesium vapor. This vapor converts them into $1S_{1/2}$ and $2S_{1/2}$ atoms by charge exchange [DO-64]. Any charged particles left are then deflected by an electric field. The atoms pass through a spin filter [MC-68] that "quench" all of the $2S_{1/2}$ atoms to the ground state except those in a specific electron-proton spin configuration. The allowed spin configuration for this experiment was N-type. This means that the spin vector of the proton, defined by the right-hand rule, pointed perpendicular, or normal, to the scattering plane, and perpendicular to the beam. The other possible directions are horizontal, or sideways (S-type), in the scattering plane, and along the direction of the beam, or longitudinal (L-type, as in $C_{LL}(\theta)$), as discussed above. Next the atoms pass through an argon cell [DO-65] that preferentially ionizes by collisions those atoms in the $2S_{1/2}$ state, but also ionizes some unpolarized atoms in the ground state. The negatively charged (H-) beam is then accelerated in a 750 kV Cockcroft-Walton (C-W) accelerator. The beam from the C-W is injected into a drift-tube

linac, and from the drift-tube into a wave-guide linac for final acceleration.

After the linac accelerates the beam to the desired energy, the ions enter the beam switchyard (figure 1). Here part of the beam is sent down the Line B tunnel, as shown in the figure. In Line B the beam encounters a stripper foil with a hole in it smaller than the size of the full beam. All of the ions that pass through the stripper material lose their electrons and continue down Line B. The ions that pass through the hole are magnetically deflected down another tunnel to the External Proton Beam (EPB) area, where this experiment was carried out. Before getting there, the beam went through a superconducting solenoid that changed it to an S-type polarization and then through three dipole magnets and another stripper foil that changed it to positively charged particles (H^+) with L-type polarization, as desired. The spin vector could now be aligned either parallel or anti-parallel to the direction of the beam, with the alignment depending on the configuration allowed by the spin filter. The spin direction was reversed once a minute during the data taking to reduce the possibility of systematic errors.

At this point the beam entered the EPB area where the scattering target and various detectors were set up. All of the apparatus were surveyed into position to assure proper placement. The configuration of the equipment is shown in figure 2. Some of the apparatus shown in the figure were used for another experiment done concurrently with the

Figure 1.

Diagram of LAMPF beam switchyard showing experimental beam area "B". The experiential setup used in this measurement was on the right-hand side of this area.

Figure 2.

Diagram of experimental setup. S and BA denote scintillation counters, and p denotes proportional wire chambers. PPT is the polarized proton target, and T denotes the transmission counters used in the $\Delta\sigma_L$ measurement. The $C_{LL}(\theta)$ events were detected in the P1L, P2L, P1R, P2R chambers. The LH₂ polarimeter was used as one of the monitors of the beam polarization.

$C_{LL}(\theta)$ experiment.* The detectors labeled S0, S1, and S2 were made of scintillating plastic connected by a light pipe to a photomultiplier tube. S1 and S2 actually consisted of two detectors each, in that S1 had an up and down half and S2 had a left and right half, with the midline of the two halves centered on the beam line. These split detectors were used to center the beam on the target. Following these detectors were two halo veto counters, BA1 and BA2, in the form of scintillators with a 1.4 cm diameter hole in them that was a little smaller than the 2.0 cm diameter target. Two photomultiplier tubes were used on the veto counter closest to the target, BA2, to improve its efficiency. These holes were centered on the beam line, so that a signal from one of the counters meant that the particle would miss the target. The placement of the holes with respect to the target was checked by putting a tungsten rod in their centers and running the beam, which was electronically centered on the S1 and S2 counters, while an undeveloped polaroid film was taped on the far side of the target cryostat from the counter. When the picture was developed, one could clearly see the tungsten rod and the target canister aligned with each other and centered on the beam spot.

* As mentioned above, this additional experiment was a measurement of the difference in the total cross section $\Delta\sigma_L$ for beam and target protons in parallel and antiparallel longitudinal spin states; it is described in [AU-81] and will not be discussed here.

The signals from the S0, S1, S2, BA1 and BA2 detectors were combined electronically to form a part of the read-in trigger, given by

$$\text{BEAM} = (S0 \cdot S1 \cdot S2) \cdot (\overline{\text{BA1}} + \overline{\text{BA2}}).$$

The symbol $\cdot$ stands for logical AND, while an overbar stands for NOT, and $+$ stands for logical OR. The circuit diagram for the electronics is shown in figure 3.

The devices in figure 2 labeled P1L, P2L, P1R and P2R were multiwire proportional chambers (MWPC's) [NI-77]. These consisted of 60-mil gold-plated tungsten wires spaced 2 mm apart in the horizontal and vertical directions. The horizontal and vertical wire planes were spaced about 1 cm apart and kept at ground potential. Each wire plane had a high voltage (~ 4000 V) plane made of aluminized mylar separated from it by about 0.64 cm. A gas mixture containing 65% argon, 34.5% carbon dioxide and 0.5% freon 13 B-1 was circulated between the wire planes and the HV planes. When a charged particle passed through the chamber, it caused the gas to ionize. This produced a current flow between the wires and the plane. The wires that gave signals were said to be "hit" by the particle and their spatial positions could be used to find the position of the particle as it traversed the chamber.

The MWPC's were used to measure the spatial coordinates of the scattered and recoil protons from elastic collisions between the beam and target protons. Behind the second MWPC on each side were two

scintillation detectors. These were used with the beam signal to trigger the data to be read into a computer, as described below. The circuit diagram for this portion of the logic is shown in figure 4. The logical formula to give a read-in signal was

$$\text{trigger} = \text{BEAM} \cdot (\text{S1L} + \text{S2L}) \cdot (\text{S1R} + \text{S2R})$$

This trigger could be vetoed by a computer busy signal and had a dead time delay veto in it. This allowed the chambers to return to normal and the electronics to be cleared after an event was read in.

In between the beam detectors and the scattering chambers lay the polarized proton target and its associated hardware. The protons in the target were polarized by the method of dynamic nuclear polarization [AB-78]. This method entails taking a material with hydrogen atoms and doping it with molecules or atoms that have an unpaired electron (i.e., with a radical). The material is then put in an intense magnetic field and kept at a low temperature. The magnetic field causes the radical's electron orbital moment to align itself along the direction of the field. The material is bombarded with photons at a frequency (in the microwave region) such that the absorption of a photon provides enough energy for the radical's electron orbital moment to flip only if a proton flips also. So when the radical flips it must take one of the surrounding protons with it. Since the coupling between the orbital magnetic moment and the proton's magnetic moment is weak and the relaxation time for the proton is much longer than for the orbital moment, the orbital moment can flip back without the proton. The direction in which the proton

Figure 4.

Schematic of $C_{LL}^{(0)}$ electronics. Inputs on left are combined to form trigger for $C_{LL}^{(0)}$ readin, labled EV6 on middle right side. The symbols are the same as in figure 3.

flips is dependent on the energy of the bombarding photon. In this way the target can be polarized either in the direction of the field or in the opposite direction by the choice of frequency of the microwaves. The target polarization was changed frequently during data taking; this took several hours and was done to reduce systematic errors.

The target material consisted of ~ 2 mm-diameter beads formed from frozen 1,2-propanediol that was doped with potassium dichromate. The beads were held in a Teflon canister with a length of 5.5 cm and a diameter of 2 cm. Teflon was used because it has no free protons. During the experiment, the target was kept at a temperature of less than 0.5°K to aid in the polarization process. To maintain this low temperature the target was held in a cryostat and constantly cooled by a ^3He refrigerator. The cryostat was held in a superconducting magnet called HERA [DE-67]. This magnet was made at the Center for Nuclear Studies at Saclay, France, and consisted of a split coil solenoid in a Helmholtz configuration which developed a 2.5-T field constant to within 0.8 mT inside the volume of the target. The target was in a microwave cavity attached to a waveguide which directed microwaves with a frequency of ~ 70 GHz onto the target material and then to two detectors used to measure the intensity of the microwave signal after it had gone through the target. The absorption of this signal was used to determine the target polarization [AB-78].

The last apparatus through which the beam passed was a polarimeter setup. This consisted of a bending magnet to rotate the spins of the protons to S-type, a lead collimator to block out any scattered particles, and a liquid H₂ polarimeter [SP-81].

Three polarimeters were used in this experiment to determine the beam polarization by measuring the asymmetric scattering of the beam from a target material, such as liquid hydrogen or CH₂. (Two of these, in Line B and in EPB, are described in a LAMPF reference [MC-80].) The asymmetry in the scattering is due to the strong interaction involving the proton's spin. Because of symmetry considerations, only S-type or N-type components of the beam scatter asymmetrically. Each polarimeter measured the asymmetry in the number of particles scattered left and right and also up and down. Using these numbers, the normal and sideways components of the beam can be calculated. The formulas for the asymmetry calculations are

$$\epsilon_s(\theta) = \frac{L - R}{L + R}$$

for S-type components and

$$\epsilon_n(\theta) = \frac{U - D}{U + D}$$

for the N-type component, where ϵ is the calculated asymmetry and L, R, U, and D are the number of particles scattered in the left, right,

up, and down directions, respectively, and θ is the angle at which the detectors are placed. To use ϵ to determine the beam polarization, the analyzing power $A(\theta)$ of the scatterer must be known. The formula for the analyzing power is

$$A(\theta) \approx \epsilon(\theta)/P_B.$$

To find A , another means of calculating the polarization is needed. The principal means used at LAMPF is called the "quench" method [MC-81]. This method takes advantage of the special characteristics of the Lamb-shift ion source described earlier. The quench measurement assumes two conditions to be true, that the background output from ground-state atoms in the argon cell remains constant and that the polarization of the beam does not change in the beam line. Evidence for the validity of these assumptions is given in the paper describing the polarimeters [MC-80]. The beam is composed of ions resulting from two actions of the argon cell, the ionization of excited atoms (which are polarized) and the ionization of ground state atoms (which are unpolarized, so that they constitute background). To measure the beam polarization the spin filter is detuned so that it forces all excited atoms to the ground-state. If the argon cell receives no excited atoms, its total output is due to the ionization of ground-state atoms. This means that the intensity measured under these conditions corresponds to the unpolarized background in the beam. When the spin filter is retuned, the added

intensity must be due to the polarized protons. The polarization of the beam (P_B) is then given by

$$P_B = \frac{I_t - I_{ut}}{I_t}$$

where I_t is the intensity measured when the spin filter is tuned, and I_{ut} when the filter is untuned.

During the data taking, ϵ was measured in two places: at the LH_2 polarimeter near the end of the experimental setup, and with the part of the beam that continued down Line B, using the LB polarimeter. The two measurements should have given the same results since they involved different parts of the same beam. There was consistently a slight difference ($\sim 2\%$) in the values, though. This was attributed to the fact that the EPB beam was taken from the middle of the original beam, while the LB beam was the remainder, outside of the middle. The target used with the polarimeter in the EPB tunnel was removed from the beam line during data taking because it could not measure the polarization of an L-type beam and would also contribute to an increase in the beam spot size due to multiple scattering. It was used occasionally to calibrate the LH_2 polarimeter and to tune the beam to L-type polarization, however.

The signals from the various detecting devices were sent by coaxial cables to a trailer containing the electronics used to analyze and record the data. The first devices on this path were standard electronic modules used in nuclear physics (NIM modules). These modules transformed the analog signals into digital ones suitable for logic operations and storage on digital devices. They also collected the various signals and combined them according to the logical equations given earlier. The NIM modules triggered another set of electronics, called CAMAC modules [ZA-72], to read the data presented to them into a PDP-11/34 computer. This computer was used to perform some online analysis and to write the information to tape for later analysis. For the $C_{LL}(\theta)$ analysis, this information consisted of MWPC data, some time of flight data (that were not used), information about the spin direction of the beam (normal or reverse), and data from the polarimeters.

The collection and online analysis of the data were controlled by a standard software package written at LAMPF called "Q" [KE-78, KE-79]. This package included routines to communicate with and control the CAMAC electronics, to handle the data from the electronics, to call user-provided routines to analyze the data, to display the data in histogram form, and to store the information on tape. This software package is discussed in the next section.

DATA REDUCTION

The analysis of the $C_{LL}(\theta)$ data was performed at New Mexico State University, on a PDP 11/60 computer, using the "Q" software package. The "Q" system was designed both for use in acquiring data online, as has been mentioned above, and for replaying that data at a later time for a more thorough analysis. This makes for a very large amount of code, most of which was not needed for replay.

A lot of the "Q" software was concerned with reading in the data, putting it in a form for analysis, and calling the needed routines. These routines have been documented in several LAMPF publications [KE-77a, KE-77b]. Only those used extensively in analyzing the data will be discussed here. Two parts that did see much use were the ALTEST package [AM-78] and the graphics package, DSP [RI-77].

The ALTEST package provided a means of testing the characteristics of an event and rejecting it if the event did not pass the criteria set up to recognize an elastic collision with a proton in the target. These criteria were in the form of a sequence of tests on the size of a measured or derived variable, or on whether a bit in a given word was set, together with logical combinations of previous tests.

The display package DSP took quantities calculated in the analysis routines and presented them graphically in the form of histograms displayed on a Tektronix 4010 video terminal. Examples of the types of variables displayed were wire maps of the X and Y planes of all the chambers and calculated quantities, such as the angles between particle trajectories (figure 5). The information displayed could be limited to events that passed specific cuts corresponding to various tests in ALTEST. Cuts could also be defined on a given variable shown in a histogram by using the cursor on the Tektronix terminal to define the upper and lower bounds (the gate) on the value of this quantity.

Another useful part of DSP was the routine PEKFIT [SL-77]. This used a least-squares fitting routine to calculate the position, width and area of a peak in the histogrammed data and the background under it (figure 6). In this procedure, the cursor was used to designate four points on the horizontal axis of the histogram. The space between designated points one and two was taken to contain background events on the left side of the peak, the space between points two and three was taken to be the peak, and that between points three and four was the right side background. The number of events between points one and two, and three and four, were counted, and the results were used to make a least-squares fit to a horizontal straight line for the background under the peak. The actual number of counts in the peak minus the background was then found, with a statistical error calculated from the combination of the number of events in the peak

Figure 5.

Histogram of $\Delta\Phi_0$. The marks labeled 1, 2, 3, and 4 are at 168° , 173° , 187° , and 192° respectively, show positions of cuts. The scale of the Y axis is from 0 to 62 counts.

Figure 6.

Histogram of calculated beam energy showing PEKFIT. The area under the fitted curve was found to be 1135 ± 48 counts by the peak fitting program, and the center of the peak was found to be at 287 ± 25 MeV compared with the expected value of 302 MeV. Scale of the y axis is 0 to 125 counts.

and the number of background events. This was the quantity used to calculate $C_{LL}(\theta)$ and its error. Next the mean and the moments about the mean of the curve were calculated. The vertical cursor was then placed near what was thought to be the peak of the histogram. This information was used to fit a curve to the data using a least-squares calculation. The fit returned various values, of which the ones used were the position of the peak and the full width at half maximum. It should be noted that in the $C_{LL}(\theta)$ calculations, no fitting was done other than to calculate the background, since the only quantities needed were the number of good events.

In replay the "Q" software read data from tape containing information about each event. It put this information in a memory location accessible to other programs. The subroutine PROC06, the controlling routine for the analysis of this event, was then called. PROC06 in turn called the subroutines TADC1, UNPAK1, GROUP1, WIRMP1, and TRACKS [DI-80]. These routines each manipulated a part of the data and returned some information to be histogrammed. TADC1 decoded information concerning the time of flight of the particles. The signals from the electronics for this information were not reliable enough to use, so these data were ignored in the analysis. UNPAK1 decoded the signals given by the MWPC's into numbers corresponding to individual wires. GROUP1 looked at the spatial grouping of the signals from the wires. As a particle passed through the chamber, it could initiate signals in many adjacent wires. For this experiment only groups of three wires or less were accepted, as more than that

might be due either to a malfunction or to more than one particle passing through. GROUPl returned values corresponding to relative positions of the tracks within the wire chambers, which should have been good to ± 1 mm, half the distance between two wires. WIRMP1 turned these numbers into quantities suitable for histogramming. The last routine, TRACKS, took the position number and, if there was one and only one hit in each of the four scattering chambers, turned it into spatial positions in the lab frame of reference. It also projected the chamber positions back to the target and calculated some other useful quantities discussed below.

Two coordinate systems were used for analysis in the lab frame, rectangular and spherical. Both systems had their origins at the center of the magnetic field of HERA (the center of the target). In the rectangular system, positive z was defined to be the direction of the beam, positive x was horizontal and to the left when facing in the positive z direction, and positive y was up. For the spherical system, the z axis remained the same, θ was defined as the angle between the positive z axis and a radial vector, and ϕ as the angle between the projection of the vector on the x - y plane and the positive x -axis.

To make sure that one had an elastic event, there was a need to find the angles between the two particles. It was also important to know where the particles came from, so as to make sure they resulted from an interaction with the target, and not a piece of the apparatus.

This would be a trivial problem if it were not for the effect of the 2.5 T magnet, HERA, used in polarizing the target. The effect of this field was to alter the trajectory of the protons from a linear path to a spiral. The slope of the spiral depended on the proton's momentum and its motion with respect to the magnetic field. Finding the initial conditions of the collision was complicated, as the solution of the differential equation of motion of a charged particle in a magnetic field is difficult and time consuming.

The method used to get around this difficulty was based on a procedure by H. Spinka of Argonne National Laboratory (ANL) [SP-80]. It uses a computer routine to solve the initial value problem of the motion of a particle through a magnetic field. Many such routines exist for this problem, two of which were used in a study of this analysis. The two routines were used as a check on each other and were found to agree to three digits. One was supplied with the magnet [JA-80], and the other was a routine written at ANL [HO-80] and uses a fourth-order Runge-Kutta scheme to solve the differential equation. Both programs used a map of the magnetic field [DE-67] that came with the program supplied with the magnet.

These computer routines were used to develop a data set of calculated tracks through the magnetic field that originate from the volume of the target and pass through positions corresponding to the scattering chambers. The initial position of the scattering interaction in the target (XT, YT, ZT) and the initial angles (θ , ϕ)

of the track were randomly generated by a Monte Carlo routine written here for the DEC PDP-11/60 and called MONTE. The random number generator used was one supplied as part of the DEC software. For each angle θ that was chosen, a momentum for the outgoing particle corresponding to the kinematics of p-p elastic scattering was calculated from the angle and the beam energy. These values were then used as initial conditions in the routine to develop a track. Tracks that did not go through the chambers were discarded; the ones that did go through both chambers had their chamber positions (X_1 and Y_1 , front chamber, X_2 and Y_2 , back chamber) and initial values written to a file. The track developing routines were used to calculate 250 different tracks through each set of chambers. The theoretical trajectories were used as a data set for a least-squares fit of a linear polynomial,

$$\Delta = A + B(X_1) + C(Y_1) + D(X_2) + E(Y_2)$$

where Δ was the quantity to be found, (X_1, Y_1) and (X_2, Y_2) were spatial coordinates of the beam track at the scattering chambers, and A through E were calculated coefficients. A computer routine based on the Crout algorithm and written at ANL [SP-80] was used to invert the matrix used in the fit.

The values fitted with this method were correction factors to a linear approximation, calculated from the scattering chamber positions, for the initial values, Y_0 , Z_0 , θ , ϕ , where Y_0 and Z_0 are

the Y and Z positions of the path at $X=0$, and Θ and Φ are the initial angles as defined above. To get the corrected approximations of the initial conditions, a straight line was calculated using the chamber coordinates of one set of chambers, left or right. The chamber coordinates were then used with the calculated coefficients to get the correction factors which were then added to the linear approximations to produce the final values.

During the calculation of the coefficients of the polynomials, a check of the corrected values to the theoretical values was made and the average absolute error was found. These errors, in the worst case at 300 MeV, were found to be $\sim 0.2^\circ$ in Θ , $\sim 0.7^\circ$ in Φ , ~ 0.07 cm in Y_0 , and ~ 0.15 cm in Z_0 . These values are felt to be very reasonable considering the accuracy of the measurements and the use to which the results were put.

Once the initial conditions were found, they were put to use in finding several other useful quantities. A linear approximation was used to find the shortest distance between the trajectories of the two scattered protons, called the distance of closest approach (DCA). The DCA should be zero for a collision, but due to inaccuracies in measurement of the trajectories and errors in the corrections for the magnetic field, it was found generally not so. The DCA was still a useful measure of quality of the event, and in the analysis, events with a DCA of up to three centimeters were accepted. A histogram of some sample values of the DCA are shown in figure 7. The next values

Figure 7.

Histogram of DCA. Values are offset by one centimeter, so where peak starts is DCA = 0 cm. Mark 2 is at DCA = 3 cm. The scale of the y axis is from 0 to 500 counts.

found were the coordinates of the collision positions, taken to be in the center of the line between the points of closest approach on the two trajectories. Histograms of these quantities are shown in figures 8, 9, 10. Also calculated were $(\theta_L + \theta_R)$ in the center-of-momentum reference frame (figure 11), the difference between the ϕ angles of the two trajectories ($\Delta\phi$, shown in figure 5), and the energy of the beam (figure 6), given kinematically by

$$T_B = 2M_P \left(\frac{1}{\tan\theta_L \tan\theta_R} - 1 \right).$$

The six quantities, $(\theta_L + \theta_R)_{cm}$, $\Delta\phi$, XT, YT, ZT and DCA, all were found to have values consistent with what is expected for an elastic collision in the target. Both $(\theta_L + \theta_R)_{cm}$ and $\Delta\phi$ should be π radians; the collision positions should be inside the target volume; and, as has been stated before, the DCA should be zero. The energy of the beam was also a known quantity and thus could be compared with the calculated value. The calculated value of the energy, when compared with the known value, was found to be a very sensitive measure of the quality of our analysis. It was used extensively as a flag during debugging of the software.

Figure 8.

Histogram of X axis values of the interaction positions. Marks 1 and 2 at -2.5 cm and 2.5 cm respectively, show positions of cuts. The scale of the vertical axis is 0 to 500 counts.

Figure 9.

Histogram of Y axis values of the interaction positions. Marks 1 and 2 at -2.5 cm and 2.5 cm respectively, show positions of cuts. The scale of the vertical axis is 0 to 500 counts.

Figure 10.

Histogram of Z axis values of the interaction positions. Marks 1 and 2 at -3.0 cm and 5.0 cm respectively, show positions of cuts. The scale of the vertical axis is 0 to 250 counts. The enhancement above and to the right of the 2 mark is at the position of the target cryostat.

Figure 11.

Histogram of $(\Theta_L + \Theta_R)_{cm}$. Marks at 1 and 2 at 172° and 188° respectively, show positions of cuts. The scale of the vertical axis is 0 to 125 counts.

Figure 12.

Histogram of $\Delta\phi_B$ peaks. Marks show $\Delta\phi = 180^\circ$ for each peak. Mark 1 is for events between 79° and 81° in θ_{cm} . The other marks are for bins increasing by 2° . The vertical scale is from 0 to 31 counts.

The averaged value of θ_{cm} , derived from both the scattered and recoil proton, was used to bin the histogrammed $\Delta\phi$ numbers ($\Delta\phi_b$, shown in figure 12). The bins were in two-degree increments that started at 79° and went for ten bins to 99° . This was done to look at the dependency on θ . To find the best candidates for elastic events, gates were set on the target positions, $(\theta_L + \theta_R)_{cm}$, and the DCA. For those events that passed these gates, a histogram of $\Delta\phi_b$ was made for each spin state of the beam (normal and reverse). This distribution always showed a clear peak centered at 180° , with a background of never more than ~5% of the height of this peak. The number of events in this peak was evaluated using PEKFIT, which also gave a statistical estimate of the error in this number. For the final values of $C_{LL}(\theta)$, the same cursor positions relative to the peaks were used.

The limits on the gates used were found by studying the effect of different settings on the calculated value of $C_{LL}(\theta)$ and its error estimate. The PEKFIT program has four settings that designate three gates, as has been mentioned above. The optimum positions for these settings with respect to the histogrammed $\Delta\phi_b$ events were found by testing the 79° to 99° bin in the following fashion. The widths of the background gates (1 to 2 and 3 to 4) were arbitrarily picked. The width of the gate for the peak (2 to 3) was centered around 180° and was tested over a range of widths, each varying by 2° . After the width of the gate for the peak was found, the widths of the background gates were tested and their values were found to have little effect on the error bars or $C_{LL}(\theta)$. The limits on the gates for ZT, $(\theta_L + \theta_R)_{cm}$,

and the DCA were established by using ALTEST to cut events going into the $\Delta\phi_b$ histogram. Each of these values was tested independently. Tests were also done on XT and YT and were found to have little effect, so the gates on these values were set loosely. The settings for these gates are shown in the figures of the sample histogrammed values, figures 7, 8, 9, 10, 11, 12.

The effects generally seen going from loose to tight cuts on one variable were that $C_{LL}(\theta)$ did not change within error bars, and that the estimated error bars decreased at first, remained fairly flat, and then increased. The change in the error bars can be understood by considering the way they are found. The error estimates come from PEKFIT and result both from a statistical calculation of the error in the area of the histogrammed data and the error in the background. As the cuts are moved in at first, the number of background events is reduced, making the error bars smaller, and as the cuts are moved in further, good events are also rejected and the error bars increase. The tests on cuts were done at the two end energies, 300 and 800 MeV. The same set of values for the gates was found acceptable at both energies, so no testing was done on the intermediate energies.

As a check on systematic errors, many individual data-taking sessions or runs were recorded at each energy. For replay, each run was analyzed separately and the areas under the coplanarity curves of each bin stored on computer files. A computer program was written to read the files, calculate $C_{LL}(\theta)$ for each angular bin, and combine the

binned values from each run into an average over all runs weighted by the errors. The program then carried out a chi-squared test on each bin in each run. The chi-squared test was used to point out runs with possible errors. Those with a large value of chi-squared were examined very closely, and in some cases errors were found that were either corrected or used as the reason to discard the run. Actually only one run was discarded as a result of close examination. It was found that a fault in the electronics had caused erroneous data to be read onto the tape for that one run. Other runs were checked for this problem but it not was seen elsewhere.

A test of the distribution of the chi-squared numbers was then performed. According to Fisher [FI-58], the quantity

$$Y_2 = (2\chi^2)^{1/2} - (2n_D - 1)^{1/2},$$

where n_D is the number of degrees of freedom, should be normally distributed with unit standard deviation. To test these results, a Y_2 value was found for each degree bin at each energy. These were then plotted, and the distribution was found to be skewed to the left. After some testing, it was found that shrinking the error bars by 10% gave the expected distribution for Y_2 , shown in figure 13. On this basis the error bars were reduced by that amount. It is believed that the reason for the error bars being too large lies in the estimation of the error in the background under the $\Delta\phi$ peak.

Figure 13.

Histogram of Y_2 values, with a Gaussian curve normalized by eye.

RESULTS

The calculated values of $C_{LL}(\theta)$ with the reduced error bars are given in table I and shown in figure 14. The angular values at each energy were also fitted to the equation,

$$C_{LL}(\theta) = A + (B)\cos^2(\theta)$$

which reflects the expected symmetry around 90° , due to the indistinguishability of the scattered and recoil proton. These fitted values of A and B are shown plotted in figures 15 and 16, respectively, and given in table II. Also shown plotted with the values of A are previous results [AU-78] and phase-shift predictions [BH-81]. The satisfactory agreement of the phase-shift predictions below 500 MeV and the previous results with the new values can be seen in this figure. Interpretation of these results with respect to the nucleon-nucleon interaction is discussed elsewhere [BU-82].

TABLE I
BINNED $C_{LL}(\theta)$ VALUES OVER THIRTEEN ENERGIES

θ_{cm}	T_B	C_{LL}	T_B	C_{LL}
80°	302.9 MeV	0.540 ± 0.069	384.6 MeV	0.164 ± 0.173
82°		0.496 ± 0.032		0.278 ± 0.066
84°		0.457 ± 0.022		0.233 ± 0.051
84°		0.488 ± 0.019		0.293 ± 0.041
86°		0.502 ± 0.018		0.292 ± 0.039
88°		0.491 ± 0.017		0.292 ± 0.039
92°		0.460 ± 0.018		0.267 ± 0.039
94°		0.427 ± 0.021		0.301 ± 0.042
96°		0.518 ± 0.028		0.302 ± 0.053
98°		0.565 ± 0.064		0.461 ± 0.098
80°	434.4 MeV	-0.233 ± 0.110	485.0 MeV	0.169 ± 0.169
82°		0.238 ± 0.056		0.195 ± 0.086
84°		0.169 ± 0.045		0.158 ± 0.074
86°		0.029 ± 0.042		0.176 ± 0.064
88°		0.176 ± 0.038		0.227 ± 0.062
90°		0.192 ± 0.038		-0.011 ± 0.059
92°		0.250 ± 0.038		0.197 ± 0.067
94°		0.220 ± 0.040		0.179 ± 0.065
96°		0.132 ± 0.049		0.111 ± 0.075
98°		0.159 ± 0.096		0.307 ± 0.128
80°	518.4 MeV	0.199 ± 0.078	535.4 MeV	-0.118 ± 0.291
82°		0.106 ± 0.030		0.219 ± 0.080
84°		0.133 ± 0.024		0.195 ± 0.072
86°		0.116 ± 0.022		0.208 ± 0.057
88°		0.098 ± 0.021		0.254 ± 0.054
90°		0.107 ± 0.022		0.153 ± 0.057
92°		0.145 ± 0.022		0.150 ± 0.057
94°		0.185 ± 0.023		0.136 ± 0.063
96°		0.155 ± 0.027		0.221 ± 0.065
98°		0.185 ± 0.050		0.565 ± 0.109
80°	569.6 MeV	0.041 ± 0.082	586.3 MeV	0.135 ± 0.145
82°		0.196 ± 0.027		0.176 ± 0.052
84°		0.188 ± 0.021		0.227 ± 0.038
86°		0.178 ± 0.019		0.201 ± 0.037
88°		0.165 ± 0.019		0.159 ± 0.034
90°		0.150 ± 0.019		0.170 ± 0.034
92°		0.165 ± 0.020		0.136 ± 0.035
94°		0.194 ± 0.020		0.272 ± 0.035
96°		0.201 ± 0.022		0.209 ± 0.039
98°		0.288 ± 0.040		0.255 ± 0.066

(continued)

TABLE I (continued)

θ_{cm}	T_B	C_{LL}	T_B	C_{LL}
80°	619.8 MeV	-0.010 ± 0.102	636.8 MeV	0.059 ± 0.252
82°		0.250 ± 0.037		0.199 ± 0.083
84°		0.233 ± 0.026		0.256 ± 0.055
86°		0.191 ± 0.025		0.228 ± 0.055
88°		0.206 ± 0.024		0.171 ± 0.050
90°		0.192 ± 0.024		0.181 ± 0.046
92°		0.189 ± 0.025		0.183 ± 0.048
94°		0.241 ± 0.026		0.240 ± 0.048
96°		0.197 ± 0.030		0.323 ± 0.055
98°		0.190 ± 0.059		0.051 ± 0.098
80°	688.0 MeV	0.023 ± 0.172	739.5 MeV	-0.022 ± 0.121
82°		0.210 ± 0.054		0.142 ± 0.037
84°		0.246 ± 0.030		0.213 ± 0.018
86°		0.250 ± 0.026		0.204 ± 0.015
88°		0.219 ± 0.027		0.216 ± 0.015
90°		0.230 ± 0.025		0.242 ± 0.014
92°		0.280 ± 0.027		0.247 ± 0.015
94°		0.202 ± 0.028		0.222 ± 0.016
96°		0.234 ± 0.033		0.275 ± 0.020
98°		0.179 ± 0.060		0.175 ± 0.044
80°	790.1 MeV	0.329 ± 0.403		
82°		0.196 ± 0.170		
84°		0.222 ± 0.049		
86°		0.247 ± 0.043		
88°		0.134 ± 0.039		
90°		0.198 ± 0.040		
92°		0.118 ± 0.042		
94°		0.221 ± 0.040		
96°		0.202 ± 0.057		
98°		0.065 ± 0.124

Figure 14.

Plotted values of $C_{LL}(\theta)$. These are at the energies indicated. Also shown are the curves generated by the fit $C_{LL}(\theta) = A + B \cos^2(\theta)$.

Figure 14 (continued)

Figure 14 (continued)

Figure 15.

Plotted values of A_0 from the fit $C_{LL}(\theta) = A + B \cos^2(\theta)$. Also shown are C_{LL} values at 90° from the ZGS. The curve is a phase-shift prediction of Arndt, et al [BU-81].

Figure 16.

Plotted values of B, from the fit, $C_{LL}(\theta) = A + B \cos^2(\theta)$.

TABLE II
FITTED $C_{LL}(\Theta)$ VALUES

A	T_B	B
0.475 ± 0.007	302.9	0.953 ± 0.922
0.285 ± 0.015	384.6	0.363 ± 1.912
0.197 ± 0.015	434.4	-4.550 ± 1.634
0.131 ± 0.023	485.0	3.630 ± 2.495
0.124 ± 0.008	518.4	1.292 ± 0.918
0.171 ± 0.021	535.4	5.430 ± 2.462
0.165 ± 0.007	569.6	2.378 ± 0.807
0.180 ± 0.013	586.3	2.544 ± 1.461
0.204 ± 0.009	619.8	0.586 ± 1.081
0.205 ± 0.018	636.8	1.430 ± 2.203
0.244 ± 0.010	688.0	-1.889 ± 1.319
0.237 ± 0.006	739.5	-2.370 ± 0.843
0.172 ± 0.016	790.1	3.248 ± 2.510

SUMMARY AND CONCLUSIONS

Values of the proton-proton spin correlation parameter $C_{LL}(\theta)$ were measured at 13 energies between 300 and 800 MeV over an angular range of 79 to 99 degrees in θ_{cm} . The data for these values were taken using the polarized proton beam and a polarized proton target at the Los Alamos Meson Facility. The scattered and recoil proton were detected in multiwire proportional chambers, and the information was stored on tape.

The analysis of the data was done at New Mexico State University. This entailed reconstructing the interaction events from stored data and then requiring them to be consistent with elastic collisions. The resulting numbers were used to calculate values of $C_{LL}(\theta)$ for each run and the runs at each energy were combined into weighted averages. The error bars on the values were tested statistically and reduced as a result of the test. The values of $C_{LL}(\theta)$ from this experiment were found to be in agreement with phase-shift predictions below 500 MeV and with previous results.

ACKNOWLEDGMENTS

I would like to thank my advisor Dr. George R. Burleson for his knowledge, patience, and wisdom. He made the process of learning physics a way of learning about life. Two other people that merit an extra share of thanks for their sharing of knowledge are Dr. Hal M. Spinka and Dr. Robert Wagner. Next thanks must go to all of the other experimenters on this project, Ken Imai, Steve J. Greene, William B. Cottingame, W. R. Ditzler, Earl W. Hoffman, John J. Jarmer, Koichi Toshioka, Robert Stanek, Dave Underwood, Dan Hill, A. Yokosawa, I. P. Auer. Special thanks goes to the departmental secretaries, Nancy Denzler and Josie Vigil, for helping with things like typing and such.

REFERENCES

- [AB-78] A. Abragam, M. Goldman, Reports on Progress in Physics 41, 395 (1978).
- [AM-78] J. F. Amann, Alltest - A Data Testing Package, LAMPF MP-10 internal report, March 78 (unpublished).
- [AU-78] I. P. Auer, A. Beretvas, E. Colton, H. Hlapern, D. Hill, K. Nield, B. Sandler, H. Spinka, G. Theodosiou, D. Underwood, Y. Watanabe, A. Yokosawa, Physical Review Letters 41, 7 (1978).
- [AU-81] I. P. Auer, W. R. Ditzler, D. Hill, K. Imai, H. Spinka, R. Stanek, K. Toshioka, D. Underwood, R. Wagner, A. Yokosawa, G. R. Burleson, W. B. Cottingham, S. J. Greene, S. J. Stuart, E. W. Hoffman, J. J. Jarmer, Physical Review D 24, 2008 (1981).
- [BH-81] R. Bhandari, R. A. Arndt, L. D. Roper, B. J. Verwest, Physical Review Letters 46, 1111 (1981).
- [BU-81] D. V. Bugg, J. A. Edgington, N. Stevenson, D. Axen, R. Shypit, M. Comyn, D. Healey, J. Stanley, N. M. Stewart, Journal of Physics G 7, 225 (1981).
- [BU-82] G. R. Burleson, W. B. Cottingham, S. J. Greene, S. J. Stuart, E. W. Hoffman, J. J. Jarmer, I. P. Auer, W. R. Ditzler, D. Hill, K. Imai, H. Spinka, R. Stanek, K. Toshioka, D. Underwood, R. Wagner, A. Yokosawa, (to be published).
- [DE-67] H. Desportes, Proceedings of the Second International Conference on Magnet Technology, edited by H. Hadley (Oxford, 1967), pp. 603-610.
- [DI-80] R. Ditzler, sole author of all routines except TRACKS, partial author of that routine.
- [DO-64] B. L. Donnally, T. Clapp, W. Sawyer, M. Schultz, Physical Review Letters 12, 502 (1964).
- [DO-65] B. L. Donnally, W. Sawyer, Physical Review Letters 15, 439 (1965).
- [FI-58] R. A. Fisher, Statistical Methods for Research Workers, (Oliver and Boyd, Edinburgh and London, 1958).
- [HO-80] E. W. Hoffman (private communication).
- [JA-80] J. J. Jarmer (private communication).
- [KE-77a] M. Kellogg, M. M. Minor, S. Schlaer, N. Spencer, R. F. Thomas, H. Beken, QAL and the Analyzer Task, LAMPF internal report LA-6884-M, October 1977 (unpublished).

- [KE-77b] M. Kellogg, M. M. Minor, S. Schlaer, N. Spencer, R. F. Thomas, H. Beken, Qmodule: CAMAC Modules Recognized by the QAL Compiler, LAMPF internal report LA-6951-M, October 1977 (unpublished).
- [KE-78] M. Kellogg, M. M. Minor, S. Schlaer, N. Spencer, R. F. Thomas, H. Beken, Introduction to Q, LAMPF internal report LA-7001-M, June 1978 (unpublished).
- [KE-79] M. Kellogg, M. M. Minor, S. Schlaer, N. Spencer, R. F. Thomas, H. Beken, Q Handbook, LAMPF internal report, July 1979 (unpublished).
- [LA-69] G. P. Lawrence, G. G. Ohlsen, J. L. McKibben, Physics Letters 28b, 594 (1969).
- [MC-68] J. L. McKibben, G. P. Lawrence, G. G. Ohlsen, Physical Review Letters 20, 1180 (1968).
- [MC-80] M. W. McNaughton, LAMPF Beam Line Polarimeters, LAMPF informal report LA-8307-MS, April 1980 (unpublished).
- [MC-81] M. W. McNaughton, P. R. Bevington, H. B. Willard, E. Winkelmann, E. P. Chamberlin, F. H. Overna, N. S. P. King, Physical Review C 23, 1130 (1981).
- [NI-77] K. Nield, R. Daly, A Multiwire Proportional Chamber System and Fast Event Filter Used by the HEP-PPT Group at ANL, ANL report ANL-HEP-PR-77-32, 1977 (unpublished).
- [OH-71] G. G. Ohlsen, J. L. McKibben, G. P. Lawrence, P. W. Keaton, D. D. Armstrong, Physical Review Letters 27, 599 (1971).
- [PA-69] E. B. Paul, Nuclear and Particle Physics, (North-Holland Publishing Company, 1969) pp. 69-70.
- [RI-77] R. J. Ridge, M. A. Oothoudt, M. Gazzali, J. F. Amann, DSP - Histogram Display Program, LAMPF internal report, November 1977 (unpublished).
- [SL-77] D. Slater, S. Verbeck, M. Oothoudt, PEKFIT-- A Peak Fitting Routine, LAMPF internal report, November 1977 (unpublished).
- [SP-80] H. M. Spinka (private communication).
- [SP-81] H. M. Spinka, The LAMPF LH₂ Polarimeter, ANL internal report ANL-HEP-81-34, 1981 (unpublished).
- [WI-63] R. Wilson, The Nucleon-Nucleon Interaction, (Interscience Publishers, 1963) pp. 43-45.

- [YO-80] A. Yokosawa, Physics Reports 64, 49 (1980).
- [ZA-72] B. Zacharov, CAMAC Systems: A Pedestrian's Guide, extract from a lecture series given at the CERN Computing and Data-Processing School, Pertisau, September 1972.