Spin Correlation in Proton-Proton Scattering at 27 MeV*

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The spin-correlation parameter C_{nn} for proton-proton scattering has been measured at 90.00±0.25° c.m. angle and 27.05±0.10 MeV. The value obtained is $C_{nn}=-0.689\pm0.070$. The construction and operation of the apparatus is described, detailing the cryogenic targets and fast electronic logic. The analysis of the data is explained. Related experiments and the significance of this measurement in the investigation of nucleon-nucleon scattering are briefly discussed.

1. INTRODUCTION

IN the absence of a successful theoretical description of the strong nuclear forces, one attempts to set up a general phenomenological description of the fundamental processes such as nucleon-nucleon scattering. The phenomenological procedure for proton-proton scattering in the elastic energy range is reaching an advanced stage.[1] A variety of spin-dependent scattering experiments[2] have been done at energies in the elastic region (at roughly 25, 50, 100, 150, 200, and 300 MeV), and several energy-dependent[3–6] and -independent[6–8] phase-shift analyses have very nearly provided a complete and apparently unique description of the various data. The present experiment provides an additional scattering parameter at 27 MeV, complementing other scattering parameters recently measured[9,10] in this energy region in an attempt to establish a better basis for phase-shift analyses. The parameters A and R have been measured[10] at 27.6 MeV, and improved cross sections[10] have been determined at 25.6 MeV. There have been preliminary reports of accurate measurements of A_{YY}, the "time-reversed" C_{nn}, using a polarized beam and target from Saclay[11] at 25.7 MeV.

The spin-correlation coefficient C_{nn} is defined[12] as follows: For an unpolarized beam and target, C_{nn} is the expectation value of the components normal to the plane of the scattering of the spin of the two final protons:

$$C_{nn}=\langle\sigma_1\cdot n\ \sigma_2\cdot n\rangle.$$

This parameter, together with others measuring the expectation values of proton-proton scattering with various initial and final spin states, is used to determine the scattering matrix or, equivalently, a complete set of phase shifts.[12,13] In principle, for proton-proton scattering, 9 independent experiments at a given energy (5 if done at "all" angles) are enough to determine the scattering matrix at that energy. This ideal situation is complicated by experimental uncertainties together with the lack of sensitivity of the phase shifts to certain scattering parameters and the need for a limited number of angular momentum states at lower energies.

At a center-of-mass c.m. scattering angle of 90°, the coefficient C_{nn} has a particularly simple interpretation. In fact,

$$I_0C_{nn}=|M_t|^2-|M_s|^2,$$

where I_0 is the differential cross section and M_t and M_s are the triplet and singlet scattering amplitudes. The value of C_{nn} varies from -1 for pure singlet scattering to $+1$ for pure triplet scattering. Since I_0 is the sum of the triplet and singlet terms, the fraction of triplet to singlet scattering can be found from a knowledge of C_{nn}. The significant use of the experimental result lies, how-

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[1] For a summary and comparison of work done (to 1964) see P. Signell and N. R. Yoder, Phys. Rev. **132**, 1707 (1963); **134**, B100 (1964).

[2] The reader is referred to the various references given for information on earlier work.

[3] G. Breit *et al.*, Phys. Rev. **128**, 826 (1962); M. H. Hull *et al.*, *ibid.* **128**, 830 (1962); G. Breit *et al.*, Bull. Am. Phys. Soc. **9**, 378 (1964) and private communication.

[4] R. A. Arndt and M. H. MacGregor, Phys. Rev. **141**, 873 (1966).

[5] M. J. Moravcsik, H. P. Noyes, H. P. Stapp, and R. Wright (unpublished, and private communication).

[6] H. Pierre Noyes, D. S. Bailey, R. A. Arndt, and M. H. MacGregor, Phys. Rev. **139**, B380 (1965) and (private communication).

[7] P. Signell, Phys. Rev. **139**, B315 (1965).

[8] C. J. Batty, R. S. Gilmore, and G. H. Stafford, Nucl. Phys. **45**, 481 (1963).

[9] See Ref. 6 for a table of earlier experiments in the 25-MeV region.

[10] A. Ashmore *et al.*, Nucl. Phys. **73**, 256 (1965); C. J. Batty, G. H. Stafford, and R. S. Gilmore, *ibid.* **51**, 225 (1964).

[11] A. Abragam *et al.*, Phys. Letters **2**, 310 (1962); P. Catillon, M. Chapellier, D. Garreta, and J. Thirion, in *Proceedings of the International Conference on Polarization Phenomena of Nucleons, Karlsruhe, 1965*, edited by P. Huber and H. Schopper (Birkhäuser Verlag, Basel und Stuttgart, 1966).

[12] Michael J. Moravcsik, *The Two-Nucleon Interaction* (Oxford University Press, New York, 1963).

[13] L. Puzikov, R. Ryndin, and J. Smorodinsky, Nucl. Phys. **3**, 436 (1957).

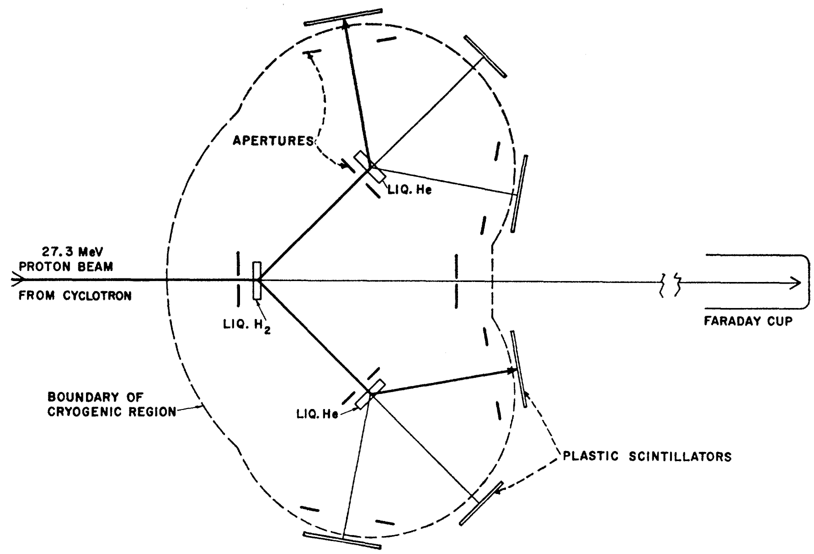

FIG. 1. Schematic diagram of the experimental arrangement. The heavier lines indicate the path of a typical triple scattering coincident proton pair.

ever, in its contribution to the complete phase-shift analyses.

This experiment determines the coincident spin states normal to the scattering plane of an unpolarized 27-MeV beam of protons scattering off an unpolarized proton target at the c.m. angle of 90°. Other angles were not measured because of the experimental difficulty and because the angular variation at low energies was not expected to be useful.[14] A preliminary report of this work has been published.[15]

2. EXPERIMENTAL METHOD

The general experimental schematic diagram is shown (looking down) in Fig. 1, and the labeling key for the counters is shown in Fig. 2. A beam of unpolarized protons from the University of Colorado cyclotron strikes an unpolarized liquid-hydrogen target. Protons from the hydrogen target scattering at approximately 45° in the laboratory strike liquid-helium analyzers and scatter again into scintillation detectors. Electric pulses from the detector photomultiplier tubes are fed into a logic of fast-coincidence circuits. To determine the accidental rate, the various coincidences (LL', LR', etc.) are recorded for both true timing and also for the case where one pulse is delayed by one cyclotron period. Various singles and other counting rates are also recorded.

For a geometry of point targets and detectors, it can be shown from the definition of C_{nn} that a triple scat-

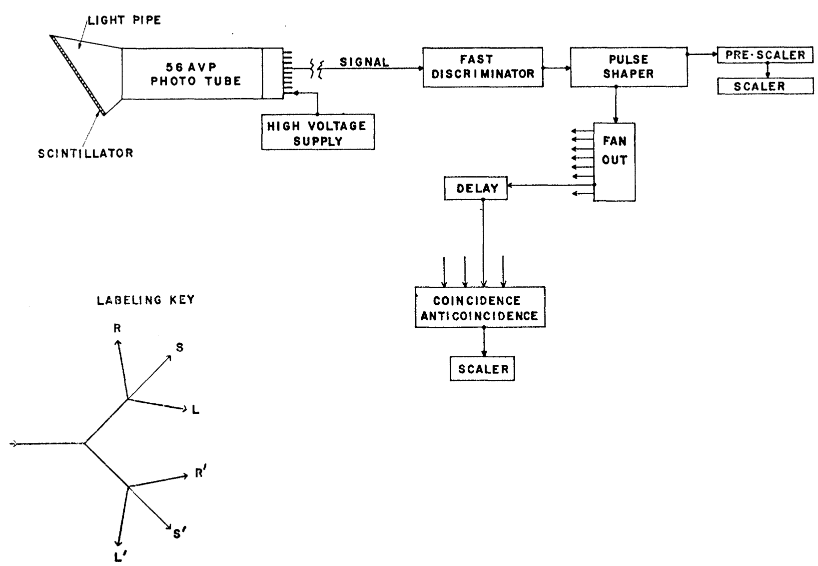

FIG. 2. Schematic diagram of a typical section of the fast electronic logic and one of the detectors. The labeling key is for use in discussing the various coincidences in the text.

[14] J. Iwadare, Proc. Phys. Soc. (London) **78**, 185 (1961).
[15] N. Jarmie *et al.*, Bull. Am. Phys. Soc. **10**, 1204 (1965).

tering coincidence counting rate (for example, LL') is

$$LL'=C(1+C_{nn}AA'),$$

where C contains geometric and target factors and initial beam intensities, and A and A' are the analyzing powers of the helium analyzers. This expression has been simplified by the fact that at these energies the polarization in proton-proton scattering is very small.[16] The experimental value sought is ϵ, which is defined as

$$\epsilon=\frac{LL'+RR'-LR'-RL'}{LL'+RR'+LR'+RL'},$$

and by substituting for LL', LR', etc., one finds (for point geometry)

$$C_{nn}AA'=\epsilon.$$

Because of the very low counting rates expected, the targets were designed to be relatively thick and the solid angles were designed to be large. The relationship between C_{nn} and ϵ is then not simple and depends on the variation of the analyzing power with angle and energy, geometrical correlation asymmetries, multiple scattering in the targets, and so forth. A Monte Carlo computer program (see Sec. 5 and the following paper) was written to establish the relationship between C_{nn} and ϵ using the known sizes of the apparatus and measured proton-alpha cross section and polarizations.

The purpose of the design of the apparatus was to force rigidity and alignment of the various targets and slits in the initial construction instead of depending on later alignment. All important apertures and targets were carefully machined and rigidly mounted on a master plate. Both helium and hydrogen targets were liquid lamina about 2-mm thick. The initial beam was constrained by apertures to a radius of 1.0 mm; the solid angle of the hydrogen scattering was roughly 10^{-2} sr ($3°\times3°$); the distance between the hydrogen and helium targets was 9 cm; the solid angle of the helium scattering was about 0.16 sr; the distance from the helium target to the scintillator was about 7 cm; the radius of the scintillators was 1.6 cm; and the range of proton energies striking the detectors was 3 to 11 MeV. Further details are given below.

3. APPARATUS

The master plate holding the targets and apertures was rigidly attached to a 20-liter liquid-helium reservoir. Liquid-helium loss was monitored by passing the boil-off gas through a gas meter. One filling lasted 13 to 16 h depending on the beam level. Most of the heat loss was in the supports. The chamber vacuum varied from less than 10^{-7} to 10^{-6} Torr. Attached to and surrounding the target-aperture system was a liquid-helium-cooled temperature shield. Surrounding the entire liquid-helium temperature system was a liquid-nitrogen-cooled temperature shield. Surrounding the liquid-nitrogen temperature system was the main vacuum jacket to which were attached the detector systems and the beam pipes. Particle passage from the target area to the detectors traveled through thin aluminum foils in the various thermal shields. The entire cryostat assembly was 14-ft high, weighed 1600 lb, and was mounted on bearings to enable remotely controlled motion for all degrees of freedom for precise alignment.

For a point-geometry system, all protons entering one helium target would have a mate entering the other helium target. For the finite geometry actually used, this is not true. One of the major design considerations was to find the best compromise among the counting rate, angular resolution, and the effect of the unmated protons. In the final geometry, 12% of the protons entering counter S or S' (see Fig. 2) did not have mates on the other side.

A. Beam

The cyclotron beam was shaped by apertures in a radiation shield wall 30 ft from the hydrogen target such that the resultant beam could be focused onto the apertures in the main apparatus with a minimum of beam striking the apertures and slits near the experiment. This design proved important for low background rates. Two apertures before and after the liquid-hydrogen target determined the alignment of the beam. These apertures were divided into quadrants which were electrically shielded. The currents of scraped beam could be monitored during the experiment ensuring optimum alignment, maximum transmission, and minimum background. To minimize neutron production, these quadrant apertures as well as the final Faraday cup were made of carbon; nevertheless, most of the neutron background came from the first quadrant aperture.

The beam was pulsed with the cyclotron separation of about 50 nsec, and the coincidences accepted any events in one pulse (about 2 nsec wide) as simultaneous. The intensity modulation of the beam pulses was important in its effect on the delayed coincidence. Studies showed that the modulation was smooth, and only a small correction was needed in the delayed coincidence data. The energy of the beam was measured in a separate chamber by the "crossover" technique.[17,18]

B. Hydrogen Target

Details of the hydrogen target are discussed in a separate paper.[19,20] The separation between the target

[16] P. Christmas and A. E. Taylor, Nucl. Phys. **41**, 388 (1963).

[17] B. M. Bardin and M. E. Rickey, Rev. Sci. Instr. **35**, 902 (1964).

[18] R. Smythe, Rev. Sci. Instr. **35**, 1197 (1964).

[19] N. Jarmie, Rev. Sci. Instr. **37**, 1670 (1966).

[20] Most of the cryogenic data used came from the following references: *A Compendium of the Properties of Materials at Low Temperature (Phase 1), Part 1. Properties of Fluids*, edited by V. J. Johnson, Report WADD-TR-60-56 (Natl. Bur. Std., U. S. Government Publishing and Printing Office, Washington 25, D. C., 1960); D. B. Chelton and D. B. Mann, University of California Radiation Laboratory Report No. UCRL-3421, 1956 (unpublished).

walls (0.0038-mm-thick Havar foil[21]) was about 2 mm. The liquid (about 7 cc) was condensed from hydrogen gas and was automatically maintained in the liquid phase at about 340 Torr pressure and 15.1°K by a system of thermocouples, heaters, and heat conduction paths to the liquid-helium reservoir. Maintenance of the hydrogen target in the liquid phase enabled it to absorb without boiling the deposited beam energy (normally 50 mW). The target was about 700-keV thick to 27-MeV protons. The hydrogen target could be moved by remote control along the line of the beam to ensure that the thin lamina of liquid hydrogen was at the precise scattering point required by the geometry. In the initial stages of the experiment, the target was translated such that the coincidence rate of the scattered proton and its recoil (SS') was maximized. The resulting position was found to be in agreement with the design geometry and the slight shift of about $\frac{1}{2}$ mm because of the small relativistic correction at this energy.

C. Helium Targets

The helium targets were similar to the hydrogen target, except that they were rigidly attached to the helium reservoir and fed directly from it. The pressure and temperature were at local boiling conditions, about 4°K and 630 Torr. The design criteria for the directions and solid angles for the spin-analysis scattering are as follows: The polar angle and angular range were chosen by maximizing the figure of merit $A^2\sigma$, as in simple spin-analysis experiments, where A is the analyzing power[22] and σ is the cross section.[23] This process resulted in a polar angle centered at 55° with an angular range of about 20°. The azimuthal angular bite was determined by the falloff of the $\cos\varphi$ term in the analyzing power[24] and was chosen to be about 25°. Depending on the angle and energies, a proton could see an analyzing power of from 0.32 to 0.76 with an approximate average of 0.51. The Havar foils were calculated to have little effect on the analyzing power.

D. Detectors

The detectors were thin plastic organic scintillators coupled to 56 AVP photomultiplier tubes by short Lucite light pipes, as indicated in Fig. 2. Metal shutters could be placed in front of the scintillator during the experiment to block out the direct particles from the helium targets. The thickness of the scintillators was no larger than the range of the most energetic particles expected (~11 MeV in the side counters). Recoil alpha particles were too low in energy to be counted.

[21] Hamilton Watch Company, Lancaster, Pennsylvania.

[22] K. W. Brockman, Phys. Rev. **108**, 1000 (1957); **110**, 163 (1958).

[23] T. M. Putnam, J. E. Brolley, Jr., and L. Rosen, Phys. Rev. **104**, 1303 (1956); Junpei Sanada, in *Nuclear Forces and the Few-Nucleon Problem*, edited by T. C. Griffith and E. A. Power (Pergamon Press, Inc., New York, 1960), Vol. II, p. 663.

[24] E. J. Burge, Nucl. Instr. Methods **6**, 101 (1960); **7**, 221 (1960).

E. Electronics

The pulses from the photomultiplier tubes were fed into a fast electronic logic[25] (see Fig. 2). The pulses were discriminated and then were formed to a standard shape for reliability in the coincidence circuit and for versatility in "fanning" the pulses. The resolution of the coincidences was set at about 4 nsec. In addition to the true and delayed main coincidences already described, counts from a variety of other singles and coincidence and anticoincidence arrangements were recorded, for example, "double scattering" coincidence LS' or a "single scattering" coincidence SS'. The discriminator levels for each counter were set by first determining the levels at which all "true" protons were accepted and then increasing the discrimination so that only 90 to 95% of the protons were accepted (a cutoff at about 6-MeV proton energy). Such a procedure minimized the background due to random accidentals because it greatly reduced the singles rates, but did not significantly distort the measured asymmetry. Equality of the counting rates at 100% proton efficiency indicated that the mechanical geometry of the apparatus was accurate.

The system was dynamically timed using pulses from protons in the actual experimental arrangement used in the final runs. Timing of the pulse routings was determined and adjusted to ±0.1 nsec. Dynamic timing was necessary in order to account for flight-time differences of the particles, photomultiplier-tube transit times, and coincidence and rise-time effects dependent on the particular shape of the photomultiplier-tube pulses. Because the transit time in the photomultiplier tube is a function of the tube voltage, pulse height adjustments were made by attenuators once exact timing of the system had been made. An attempt was made to gate the coincidences by the beam pulse. This additional coincidence requirement did not significantly improve the background rates, and it was discarded. The timing, discriminator levels, and proper functioning of the coincidences were checked at intervals during the experiment. To test the gain and other system conditions, a very small amount of ^{239}Pu was permanently deposited on the plastic crystals. Energy spectra of the resulting alphas and, during a run, of the scattered protons were checked occasionally with a multichannel analyzer.

4. EXPERIMENTAL PROCEDURE

Useful data were taken in one run lasting 8 days. The beam level was about 20 nA, determined by the arbitrary criterion that the ratio of true to accidental coincidences should be a value of about 5 or greater. Approximate values for the counting rates were 20/h for the triple scattering (LR', etc.), 10^5/h for the double scattering (LS', etc.), and 10^9/h for the single scattering (SS'). These rates agreed with the original counting-rate design. About 1200 to 1500 counts were finally

[25] Chronetics Inc., Yonkers, New York.

collected in each triple scattering coincidence channel. At these rates, the probability of more than one event of interest in one beam pulse was negligible. In order to monitor the progress of the experiment and also for later statistical analysis for possible systematic errors, data were taken in 100 units of about 1 h each. The fluctuations of the various experimental counting rates were monitored as a clue for malfunction of the equipment. The background counts in the detectors that led to accidental coincidences were shown to be due to neutrons (70%) and protons that suffered several large scatters to bypass antiscattering shields (30%).

A variety of tests was made to ensure proper functioning and understanding of the equipment. These tests included runs with the various targets empty, shutters in front of the detectors, deflected beams, variation in beam intensity, and deliberate mistiming and misalignments. Counting rate studies in counters S and S' showed that the mechanical geometry in the apertures and beam alignment was accurate to better than 1%. A permanent record was made of the beam level for use in background calculations. The total overall root-mean-square variation in the beam level was 17%. Six hundred liters of liquid helium were consumed in the final run.

5. ANALYSIS AND EXPERIMENTAL RESULT

A. Asymmetry

The number of counts in each coincidence channel gave a statistical error of 2.5%, but the subtraction necessary in calculation of the asymmetry, ϵ, leads to a higher error for the asymmetry. The final result for the asymmetry is $\epsilon = -0.122 \pm 0.015$, where the error quoted is the statistical standard deviation. This error will not propagate in a linear fashion when calculating C_{nn}. (This is discussed below.)

The background was measured directly using the delayed coincidences, or it could be calculated from the single and double scattering rates and a knowledge of the variation in beam intensity. (The coincidence resolution time does not enter since the beam pulse is completely contained in the electronic resolution time.) Both of these methods gave the same answer within statistics. Small corrections in the background were made for beam modulation (a 2% correction) and variation in beam intensity (17% correction in the calculated background). These corrections in the background became corrections in the asymmetry of at most 2%, and they did not contribute significantly to the error in ϵ.

B. Monte Carlo Computer Analysis

In order to extract a value of C_{nn} from the experimental asymmetry, the spin-analyzing power of the helium targets must in some way be unfolded. It was decided to perform a Monte Carlo simulation[26] of the experiment using the known dimensions of the target and detector system and the previously measured[27] proton-alpha cross sections and polarizations. This calculation is described in detail in the following paper.[28]

It was possible to consider making an experimental calibration of the analyzing power. Two objections eliminated this possibility. Experimental tests indicated serious background and counting-rate problems in the possible methods. More limiting was the fact that even if separate analyzing powers of the helium targets were measured, a major calculation would have to be made accounting for the spin-analysis correlations between the two helium-target systems, since ϵ is not simply proportional to C_{nn} for finite geometry. Such a calculation would be of similar complexity and reliability to the complete Monte Carlo simulation actually done.

An unexpected bonus from the simulation procedure was the use of the code to search for possible systematic errors, since in the simulation the sensitivity of the answers to artificial misalignments and other changes in the experiment could be studied. The reader is referred to the following paper for details. Such use of an experimental simulation would be invaluable in the original design of experiments, and it is suggested that, where the magnitude of the experiment merits the time and cost involved, a detailed computer simulation of an

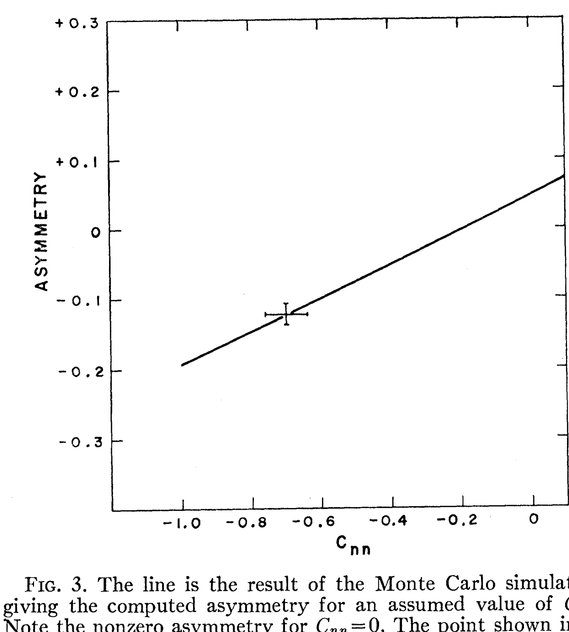

FIG. 3. The line is the result of the Monte Carlo simulation giving the computed asymmetry for an assumed value of C_{nn}. Note the nonzero asymmetry for $C_{nn}=0$. The point shown indicates how the final value of C_{nn} is determined. The vertical bar is the *experimental* asymmetry value that is measured, and the horizontal bar is the value of C_{nn} read from the graph.

[26] J. Eades, Nucl. Phys. **77**, 465 (1966).
[27] W. Haeberli (private communication).
[28] H. C. Bryant and Nelson Jarmie, following paper, Phys. Rev. **155**, 1444 (1967).

experiment be made and studied before the final geometry is determined.

The final result of the simulation procedure is indicated in Fig. 3. The line gives the computed asymmetry for assumed values of C_{nn}. The final value of C_{nn}, given in Sec. 5D, and its statistical error are found by reading from the graph those values corresponding to the experimental asymmetry ϵ and its error. An indication of one of the correlated asymmetries can be seen in Fig. 3, where for $C_{nn}=0$, the asymmetry is significantly different from zero. This zero shift, clearly, is responsible for the fact that the percent error in C_{nn} is not equal to the percent error in the experimental asymmetry, ϵ. The proper error must be read directly from the graph as indicated.

C. Errors

In the Monte Carlo calculations, the statistical counting errors involved in determining ϵ propagated through the calculation to give an 8.5% standard-deviation contribution to the error in C_{nn}. The uncertainty in the knowledge of the analyzing power contributed a 4.0% error. Another indication of error came from an analysis of the 100 separate units of data taken in the experiment. A determination of the external error from the fluctuations of C_{nn} as determined from each separate unit of data indicated a slightly larger error than can be expected from counting statistics alone. It was quantitatively estimated that there was a systematic error of about 4.0% in C_{nn} to account for the larger external error.

Folding together the 8.5% statistical error, the 4.0% error from the uncertainty in the analyzing power, and the 4.0% estimated systematic error gave a final error in the value of C_{nn} of 10.2% (standard deviation).

D. Results and Discussion

The value of the spin correlation parameter C_{nn} as determined in this experiment is then

$$C_{nn}=-0.689\pm0.070\ (10.2\%)$$

for a laboratory bombarding energy of 27.05±0.10 MeV and 90.00±0.25° c.m. angle.

Because the value of C_{nn} is expected to be constant with angle near 90° c.m. and reasonably linear with energy in the range measured, no correction needs to be made for the finite angular and energy range of the experiment.

This result for C_{nn} indicates that 84.4% of the time the scattering will occur in the singlet state. Since the Pauli principle ensures that the scattering is completely in the singlet state at zero energy (S-wave scattering) and since the scattering rapidly becomes mostly triplet at higher energies, the present result measures the growth of P-wave scattering. Thus, P-wave phases may be sensitive to C_{nn} data, and preliminary studies[6] indicate that this is so. Full significance must await more formal inclusion of the data in the phase-shift analyses.

The Saclay measurement[11] of A_{YY} at 25.7 MeV is given as -0.725 ± 0.014. A simple extrapolation of this value to 27 MeV gives a value of -0.705, in excellent agreement with our value. It seems possible that from the data of the two experiments one might extract some measure of the time-reversal invariance of strong interactions.

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