SPIN CORRELATION MEASUREMENTS IN NUCLEON-NUCLEON SCATTERING AT HIGH ENERGY

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ABSTRACT

Recent high energy measurements of spin correlation parameters are reviewed and discussed in terms of recent theoretical models.

INTRODUCTION

In this review I shall consider recent measurements of spin correlation parameters above 3 GeV/c. I have defined high energy to start at 3 GeV/c so that I can discuss an energy region which would not otherwise be covered at this conference. The region below 3 GeV/c is well covered: a large number of papers have been contributed with much new data in the range 500 MeV/c to 2.75 GeV/c and two review papers also discuss interesting phenomena in this region.

The advent of accelerated beams of polarized protons together with the availability of polarized targets has allowed rather precise measurements of the initial spin state correlation parameters such as A_{NN} and A_{LL} in elastic scattering. This has superseded the more traditional (and much less precise) measurements of the final state spin correlation parameters C_{NN}, C_{LL} etc. Of course the initial and final state parameters are equal by time reversal invariance.

At higher energies the large loss of event rate in the rescattering of both final state particles makes impossible any meaningful measurements of C_{NN} etc. Thus at high energies the only possible spin correlation measurements are in the initial state using a polarized beam and target. The only machine ever to accelerate polarized protons to high energy was the ZGS at Argonne National Laboratory which was shut down in October 1979. All the measurements I shall discuss were done at the ZGS.

SPIN PARAMETERS

Convention

I shall use the Ann Arbor Convention[1] for spin parameters. Here A_{NN}, for example, refers to a scattering asymmetry measurement in which the spins are aligned in the initial state whereas C_{NN} is obtained from rescattering the final state nucleons. The convention is not universally accepted and some groups, for historical reasons, still prefer to use C_{NN} instead of A_{NN}.

Amplitudes

I shall refer to the usual set[2] of s channel helicity amplitudes and associated t channel exchange amplitudes.

s channel	t channel
$\varphi_1 = \langle ++ \vert ++ \rangle$	$N_o = \frac{1}{2}(\varphi_1 + \varphi_3)$
$\varphi_2 = \langle -- \vert ++ \rangle$	$N_1 = \varphi_5$
$\varphi_3 = \langle +- \vert +- \rangle$	$N_2 = \frac{1}{2}(\varphi_4 - \varphi_2)$
$\varphi_4 = \langle +- \vert -+ \rangle$	$U_o = \frac{1}{2}(\varphi_1 - \varphi_3)$
$\varphi_5 = \langle ++ \vert +- \rangle$	$U_2 = \frac{1}{2}(\varphi_4 + \varphi_2)$

Observables

$$\sigma = \frac{1}{2}\left(|\varphi_1|^2 + |\varphi_2|^2 + |\varphi_3|^2 + |\varphi_4|^2 + 4|\varphi_5|^2 \right)$$

$$\sigma A = -\mathrm{Im}\left(\varphi_1 + \varphi_2 + \varphi_3 - \varphi_4\right)\varphi_5^*$$

$$\sigma A_{NN} = \mathrm{Re}\left(\varphi_1\varphi_2^* - \varphi_3\varphi_4^* + 2|\varphi_5|^2\right)$$

$$\sigma A_{LL} = \frac{1}{2}\left(-|\varphi_1|^2 - |\varphi_2|^2 + |\varphi_3|^2 + |\varphi_4|^2\right)$$

$$\sigma A_{SS} = \mathrm{Re}\left(\varphi_1\varphi_2^* + \varphi_3\varphi_4^*\right)$$

$$\sigma A_{SL} = \mathrm{Re}\left(\varphi_1 + \varphi_2 - \varphi_3 + \varphi_4\right)\varphi_5^*$$

Measurements

A spin correlation parameter A_{II} is defined in terms of pure initial spin cross sections

$$A_{II} = \frac{\left.\frac{d\sigma}{dt}\right]_{\uparrow\uparrow} + \left.\frac{d\sigma}{dt}\right]_{\downarrow\downarrow} - \left.\frac{d\sigma}{dt}\right]_{\uparrow\downarrow} - \left.\frac{d\sigma}{dt}\right]_{\downarrow\uparrow}}{\left.\frac{d\sigma}{dt}\right]_{\uparrow\uparrow} + \left.\frac{d\sigma}{dt}\right]_{\downarrow\downarrow} + \left.\frac{d\sigma}{dt}\right]_{\uparrow\downarrow} + \left.\frac{d\sigma}{dt}\right]_{\downarrow\uparrow}}$$

but since in an actual experiment the only thing which is changed for each measurement is a spin direction

$$A_{II} = \frac{1}{P_B P_T} \frac{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} - N_{\uparrow\downarrow} - N_{\downarrow\uparrow}}{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} + N_{\uparrow\downarrow} + N_{\downarrow\uparrow}}$$

where P_B and P_T are the beam and target polarizations.

Another parameter which is used is the ratio of the spin parallel cross section to the spin antiparallel cross sections, r_{II}, where

$$r_{II} = \frac{\left.\frac{d\sigma}{dt}\right]_{\uparrow\uparrow} + \left.\frac{d\sigma}{dt}\right]_{\downarrow\downarrow}}{\left.\frac{d\sigma}{dt}\right]_{\uparrow\downarrow} + \left.\frac{d\sigma}{dt}\right]_{\downarrow\uparrow}} = \frac{1 + A_{II}}{1 - A_{II}}$$

SPIN CORRELATION MEASUREMENTS IN ELASTIC SCATTERING

Small Momentum Transfer

One of the original motivations for a high energy polarized beam was for a detailed study of the dynamics of the nucleon-nucleon interaction. A major part of this effort was to obtain a complete amplitude analysis for p-p elastic scattering at small t. The various spin parameters contain different combinations of the five complex amplitudes and a measurement of a sufficient number of them enables the analysis to be made. However the structure is so rich that measurements are necessary over a range of momentum transfer and energy. Unfortunately some of the spin parameters are very difficult and time consuming to measure so a detailed study was undertaken only at 6 GeV/c and 11.75 GeV/c in order to get some idea of the energy dependence. Prior to this a large amount of data on the analysing power and a small amount on the depolarization parameter D_{NN} had allowed some limits to be put on the amplitudes.

The program was carried out mainly by the Argonne group of Yokosawa et al. and a sufficient amount of data has been analyzed to allow a reasonable description of the amplitudes. The result of such an analysis by Berger et al.[3] is shown in Fig. 1 for $-t = .4(\text{GeV}/c)^2$. Similar analyses have been carried out by Kroll et al.[4] and Wakaizumi and Sawamoto[5]. There seems to be general agreement among the analyses though they differ in details. This again is a reflection of the complicated nature of the nucleon-nucleon interaction and the fact that the errors on the measurements still leave room for maneuver.

Wakaizumi and Sawamoto contributed a paper to this conference with details of their analysis and Fig. 2 shows the fits to the various spin parameters together with the currently available data. The curves match the overall trend of the data but details of the structure are generally missed.

Experiments at small momentum transfer

One of the last spin correlation experiments to be done at the ZGS at 6 GeV/c was a measurement of A_{NN} in pp elastic scattering over the momentum transfer squared, $P_\perp^2$, range $1.0\text{-}2.4(\text{GeV}/c)^2$. Although A_{NN} had been measured earlier the data for $P_\perp^2 > 1.0$ was sparse with large errors and did not extend to 90^0 cm. It was felt necessary to fill in this gap before the end of the ZGS.

The apparatus[6] is shown in Fig. 3. The polarized beam came in from the left and entered the hydrogen target of the polarimeter. The polarimeter used two double arm spectrometers to measure the left-right scattering asymmetry in pp elastic scattering to find the beam polarization P_B where

$$P_B = \frac{1}{A} \frac{L-R}{L+R}$$

A is the previously measured analyzing power and L(R) is the total number of elastic scatters to the left (right).

After the polarimeter, the beam entered the polarized proton target. Elastic scatters from the polarized protons were detected in the two spectrometer arms F and B. Tight constraints on angle and momentum allowed the detection of a clean elastic signal.

The results are presented in Fig. 4. Considerable structure is apparent and a noticeable feature is the rapid rise to $A_{NN} \approx$ 12% at 90 cm. The predictions of three theoretical models are shown. The curves from Kroll et al. (KLS) and Field and Stevens[7] (FS) represent the data quite well up to at least $P_\perp^2 = 1.0(\text{GeV/c})^2$. The Regge Pole model of Field and Stevens is interesting because it is a prediction from several years ago before most of the spin parameters had been measured.

A somewhat neglected area before the polarized beam came along was the study of spin effects in pn scattering. The use of a polarized proton beam with a liquid deuterium target allows easier and more precise measurements of pn scattering than was possible beforehand. An early measurement by the Argonne EMS group[8] of the pn analyzing power at 2,3,4 and 6 GeV/c showed some surprising results (Fig. 5). It had been expected that either the pn analyzing power would be equal to the pp analyzing power or mirror symmetric with it depending on whether a geometric or Regge Pole approach was used. Clearly it was neither and led to a rapid reappraisal among theorists.

As a further test of the models and probe of the pn system a measurement of A_{NN} was undertaken by the Michigan-Argonne and Rice University groups. The simplest method, at least for the experimenters, was to obtain polarized deuterons from the ZGS and then to use the polarized neutron in the deuteron to interact in the polarized proton target. Using 12 GeV/c deuterons meant that the np interaction was at 6 GeV/c. The apparatus used was essentially the same as shown in Fig. 3 except that a neutron detector was used in the F arm of the spectrometer[9]. In this experiment one nucleon in the deuteron was used in the scattering while the other one continued on relatively unaffected by the interaction. The polarized neutron was allowed to interact in the polarized proton target while its paired proton continued on. The neutron polarization was measured in the polarimeter using the polarized proton in the deuteron for pp elastic scattering. The proton and neutron polarizations are equal.

In the time available it was possible to measure two data points at $P_\perp^2$ = 0.8 and 1.0 $(GeV/c)^2$ and they are shown in Fig. 6. A_{NN} in pn elastic scattering for this $P_\perp^2$ region is negative with a magnitude of ∿20%, twice as large and with the opposite sign to the pp case. The predictions of Berger et al. and Field and Stevens are shown. Again it is interesting that the older model predictions are nicely in agreement with the data while the more recent one with the benefit of a much greater body of spin measurements fails rather badly.

The data from the Rice University experiment is at lower $P_\perp^2$ and unfortunately was not completely analyzed in time for this conference[10].

At present the analyzing power for pn scattering has been measured at a number of energies over a large angular range but no data, except that discussed above, exist for other spin parameters.

Experiments at large momentum transfer

While considerable effort was going into disentangling the amplitudes at small momentum transfer, some groups were engaged in extending spin measurements out to large momentum transfer. Here the hope was that the interaction might be simpler to describe; indeed for pp scattering at 90°cm the spin flip amplitude ϕ_5 vanishes and $\phi_3 = -\phi_4$ from symmetry considerations. Further, by going to sufficiently large momentum transfer one might enter a hard scattering region where the interaction takes place between the constituents of the nucleons.

In particular, during the past few years the Michigan-Argonne group has been responsible for pushing the measurements of A_{NN} to increasingly large values of $P_\perp^2$. The apparatus used was essentially that shown in Fig. 3 and the results of this series of experiments[11] are shown in Fig. 7. The graph shows what must be familiar to many people by now, the dramatic rise of A_{NN} to a level of about 60%, close to the limits of momentum transfer available at the ZGS. This was a totally unexpected result and was subsequently interpreted as the onset of a hard scattering region where the spin structure of the nucleon constituents was being probed. In terms of r_{NN} (the ratio of the spin parallel to spin antiparallel cross sections defined earlier) a value of 60% for A_{NN} means r_{NN} = 4.

Further investigations of this effect were conducted by measuring A_{NN} for 90°cm scattering as a function of beam momentum. Again dramatic structure was seen and is shown in Fig. 8. In the region 4-8 GeV/c $A_{NN} \lesssim 10\%$; below 4 GeV/c it rises rapidly to a value of about 60%. There seems to be further structure below 2 GeV/c which has recently been investigated in more detail.[12] Above 8 GeV/c A_{NN} also rises rapidly to a level of 60%. The point at 12.75 was the highest energy at which the ZGS could be operated.

The two sets of data are combined in Fig. 9, and plotted as $r_{NN} = \sigma_{\uparrow\uparrow}/\sigma_{\uparrow\downarrow}$. Some additional data at $P_\perp^2$ = 4.5 and 5.09 are included in the 11.75 GeV/c points. The 90° cm data are plotted against the equivalent $P_{\perp}^2$ value. It is clear from the figure that both sets of data have the same structure at high $P_{\perp}^2$, suggesting that the pure spin cross sections may depend only on $P_{\perp}^2$ in the hard scattering region. It should be pointed out that if the figure had been plotted against the four momentum transfer squared the two sets of data would not have overlapped.

Inspired by these results and subsequent models which tried to explain them and make predictions for other spin variables, the Argonne group of Auer et al.[13] set up to measure A_{LL} at high $P_{\perp}^2$ at 11.75 GeV/c.

Their apparatus is shown in Fig. 10. The longitudinally polarized beam was incident on the longitudinally polarized target. The momentum and angle of the forward going particle was measured by the spectrometer magnet and planes of multi-wire proportional chambers (MWPC). A large Cerenkov counter was used for particle identification. The recoil particle was detected by MWPC's and scintillation counters. About 35% of the data have been analyzed and the results are shown in Fig. 11 together with the A_{NN} data. It is evident that as the 90 cm scattering angle is approached there is a sudden change in the structure of A_{LL}. The two sets of data should help to establish the credibility of theoretical models.

Theoretical Interpretation

If the data do indicate the onset of a hard scattering region where the scattering of the constituents is important then the ideas of QCD can be applied to try and understand the spin interactions of the constituents. QCD generally has been applied to processes at large s and t and it is not clear whether the spin data discussed above is in a region of applicability. However in the past, spin data at low energies has signalled changes which have only become evident at higher energies in spin averaged parameters (e.g., structure in the analyzing power at low energies could be related to the emergence of structure in the spin averaged cross sections at higher energies). An indication that the ideas of QCD might be applied comes from the fact that the momentum transfer region corresponds to that where the quark counting rule for fixed angle scattering cross sections applies. Here

$$\frac{d\sigma}{dt}\left(A+B \to C+D\right) = \frac{1}{s^{n-2}}\, f\left(\frac{t}{s}\right)$$

with $n = n_A + n_B + n_C + n_D$, the minimum number of fundamental constituents of the composite particles. For pp elastic scattering $n_A = n_B = n_C = n_D = 3$ and $n = 12$.

$$\frac{d\sigma}{dt}\left(p+p \rightarrow p+p \right) \approx s^{-10}\ f(\theta_{cm})$$

An overall fit to the available data gives $s^{-9.7}\ f(\theta_{cm})$.

The first attempts at fitting to the data were by Farrar et al.[14] and Brodsky et al.[15] who proposed the quark interchange model (QIM). In this simple picture quarks are interchanged between nucleons in a helicity conserving interaction which is independent of the helicity of the exchanged and spectator quarks. The model makes some specific predictions which can be tested.

The requirements of quark helicity conservation means that the amplitudes ϕ_5 and ϕ_2 are zero for all scattering angles θ_{cm} for pp and np scattering. This has the consequence

$$A = A_{SL} = 0 \qquad \qquad A_{NN} = -A_{SS} \qquad \text{for all } \theta_{cm}$$

In addition for pp scattering at 90 cm symmetry requirements have

$$\phi_5(90^0) = 0$$

$$\phi_3(90^0) = -\phi_4(90^0)$$

which leads to the model independent sum rule

$$A_{NN}(90^0) - A_{SS}(90^0) - A_{LL}(90^0) = 1$$

Therefore tests for the validity of QIM involve the measurement of A and A_{SL} for $\theta_{cm} \neq 90^0$ and require

$$A = A_{SL} = 0$$

Note that for the 11.75 GeV/c data $P_\perp^2 = 5.1\ (\text{GeV/c})^2$ corresponds to 90^0 cm

Another test is to measure directly A_{NN} and A_{SS} to check for $A_{NN} = -A_{SS}$ or to use the 90° sum rule and measure A_{LL} and either A_{NN} or A_{SS}.

From the data described above $A_{SS} = -0.6 \pm .12 \approx -A_{NN}$ which is in agreement with the idea of quark helicity conservation.

However the simple predictions for the QIM models are

$$A_{NN}^{pp} = \frac{1}{3}$$

$$A_{LL}^{pp} = A_{SS}^{pp} = -\frac{1}{3}$$

$$A_{NN}^{np} = -.44$$

$$A_{LL}^{np} = A_{SS}^{np} = .44$$

Clearly these are not in agreement with the data. The simple QIM models all obtain these results but use different approaches to generate large A_{NN}^{pp} values. Generally this means the introduction of a nonpertubative component to interfere with the main QIM process which will die away with increasing $P_{\perp}^2$. They also seem to require that in these processes $\phi_2 \neq 0$.

A number of such solutions have been proposed and the predictions of two of them are shown in Figs. 12 and 13 along with the data. The models were generated to fit the A_{NN}^{pp} data but do not agree very well with the A_{LL}^{pp} data.

An interesting attempt to justify the validity of the QIM approach was made by Wolters[16] who used a different mechanism for the quark interchange, namely backward quark-quark scattering via one gluon exchange. The other concepts are retained. Using A_{NN}^{pp} as input the following predictions are made for 12 GeV/c at 90°cm.

$$A_{NN}^{np} = -0.22 \pm .22$$

$$A_{LL}^{np} = 0.57 \pm .22$$

These have not been experimentally verified. It was pointed out by Brodsky et al.[15] that the fixed angle cross section has fluctuations around the s^{-10} prediction and that for the 90^0 cm cross section one of the more noticeable fluctuations is around 13 GeV/c. It was suggested that this might be related to the large asymmetry in A_{NN}.

Wolters has quantified this and, in his model, A_{NN} and the cross section are related such that

$$s^{10} \frac{d\sigma^{pp}}{dt} \propto \left(1 + r_{NN}^{pp}\right) \propto \frac{1}{1-A_{NN}^{pp}}$$

so that fluctuations in $s^{10} \frac{d\sigma^{pp}}{dt}$ vs. s should reflect structure in A_{NN}^{pp}. Further at 90^0 cm, $s = 4(P_{\perp}^2 + m_p^2)$ and $s^{10}(d\sigma^{pp}/dt)$ (90^0) can be plotted vs. $P_{\perp}^2$. The result is shown in Fig. 14. The prediction has been normalized to the A_{NN} point at $P_{\perp}^2 = 5.1$. Certainly the coincidence of data and prediction at high $P_{\perp}^2$ is interesting. Above $P_{\perp}^2 = 3.5(\mathrm{GeV/c})^2$ there is agreement, below there is complete disagreement. This is taken to mean that some form of QIM can be applied above $P_{\perp}^2 \sim 3.5(\mathrm{GeV/c})^2$. Interestingly the prediction shows $A_{NN} \sim 1/3$ at $P_{\perp}^2 = 10(\mathrm{GeV/c})^2$, the value predicted by the simple QIM model.

Finally I should mention an alternative approach, the massive quark model of Preparata and Soffer[17]. This has been promoted as the theory to replace QCD and the predictions for the spin variables are shown in Fig. 15. It appears to fare no better than the QIM approach.

CONCLUSIONS

I have been able to review only a small part of the considerable body of spin data which has accumulated in the past few years. The ZGS and its high energy polarized beam opened many new areas of study which have contributed greatly to our basic understanding of fundamental processes. The structure of the amplitudes at 6 GeV/c are quite well understood and there is more data to come.

Paradoxically the surprises have occurred at the low energy limit and high energy limit for ZGS beams. I have not mentioned the issue of the structure in the $\Delta\sigma_L$ measurements around 1.5 GeV/c and whether it is due to dibaryon resonances because it is a common topic at this conference and will be reviewed by Jay Roberts in the next talk. However I'm sure there will be considerable activity in the future at the lower energy machines to resolve this point.

At the highest ZGS energy and available momentum transfer dramatic structure was seen. This has been linked to the scattering of the constituents of the nucleons. However a simple approach does not explain the data. A number of predictions have been made on various spin correlation parameters but the expectation is that the simple approach is more likely to apply at higher momentum transfer. These ideas should be tested in the near future because the higher $P_{\perp}^2$ region will be accessible when the 26 GeV/c polarized beam at the Brookhaven AGS starts up in two or three years time.

In addition there are plans for a polarized beam at KEK and a 100-300 GeV/c polarized beam derived from Λ^0 decay at Fermilab, so the future for spin physics looks bright.

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(Editor's Note: Figures follow. References to this conference are given as paper numbers and are cross-indexed to page numbers in the Table of Contents.)

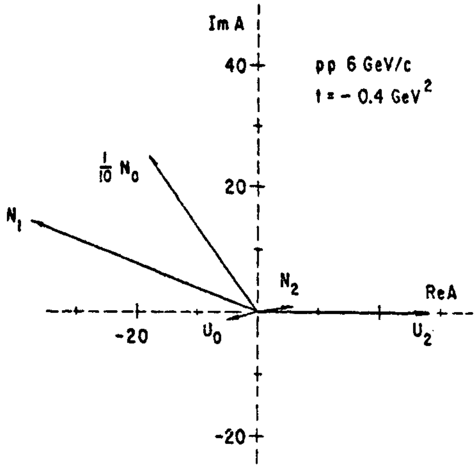

Fig. 1. Amplitude structure from Berger et al.[3]

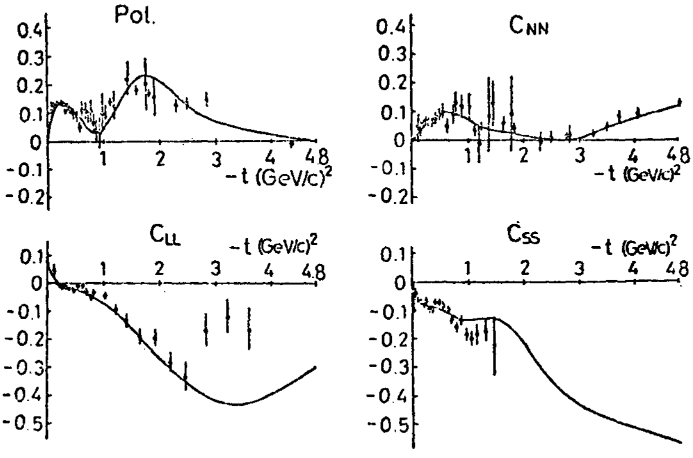

Fig. 2. Spin parameter fits of Wakaizuni and Sawamoto[5]

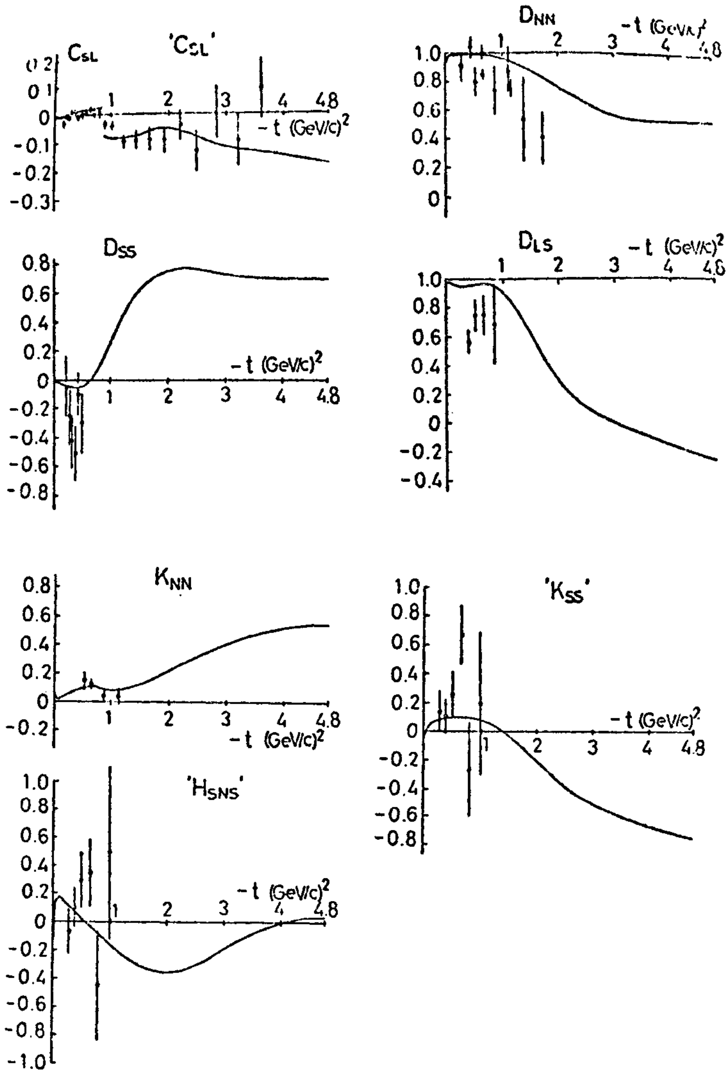

Fig. 2. Continued

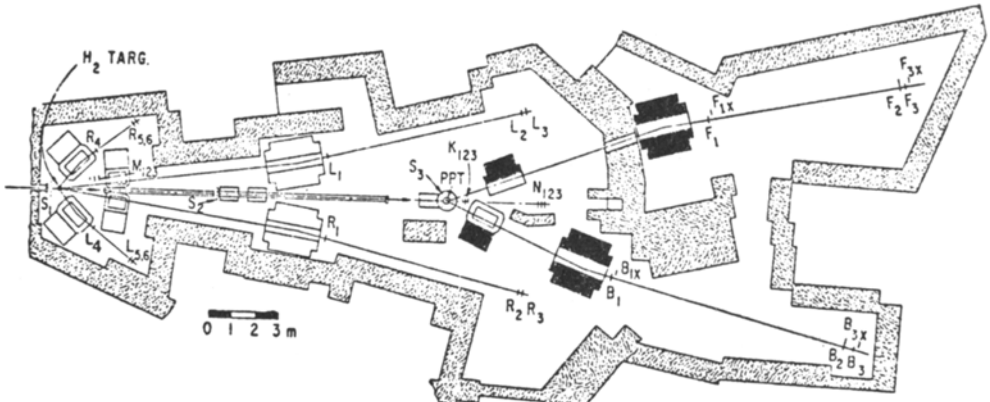

Fig. 3. Layout of the A_{NN} experiment[6]

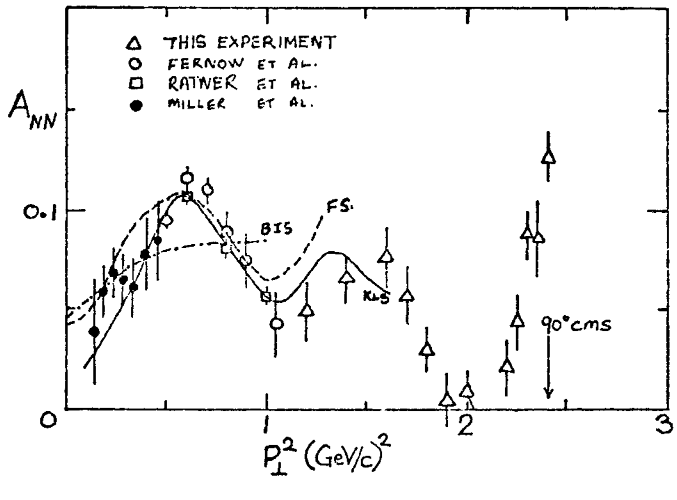

Fig. 4. A_{NN} for pp elastic scattering. The predictions of Berger et al.[3] (BIS), Field and Stevens[7] (FS) and Kroll et al.[4] (KLS) are shown.

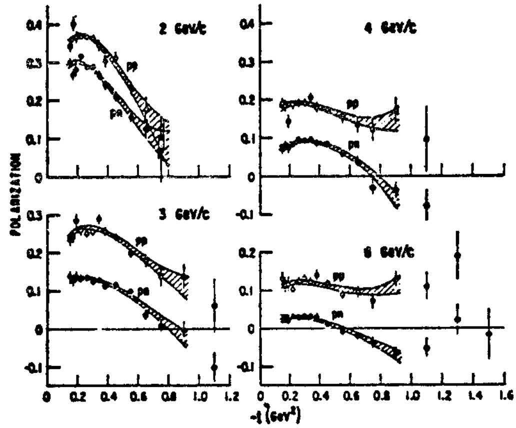

Fig. 5. Analyzing power in pp and pn elastic scattering

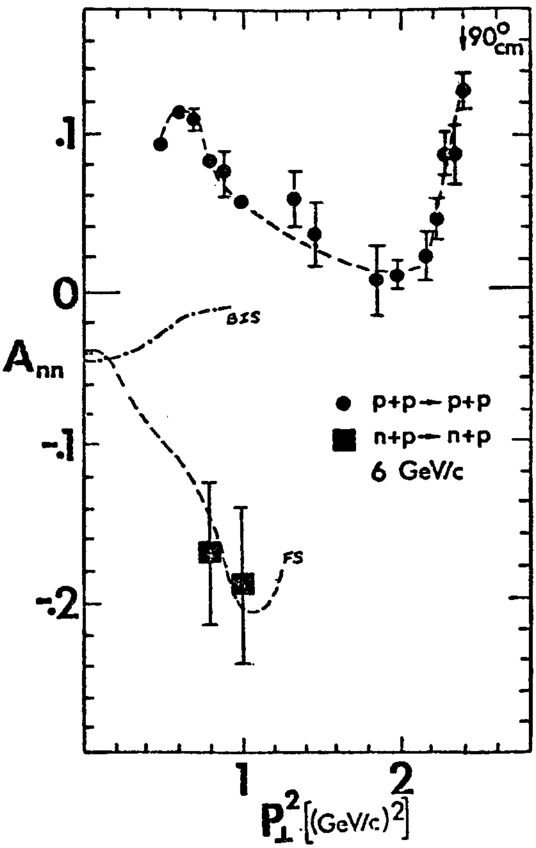

Fig. 6. A_{NN} in np elastic scattering. The predictions of Berger et al.[3] (BIS) and Field and Stevens[7] (FS) are shown. A_{NN} for pp elastic scattering is shown for comparison.

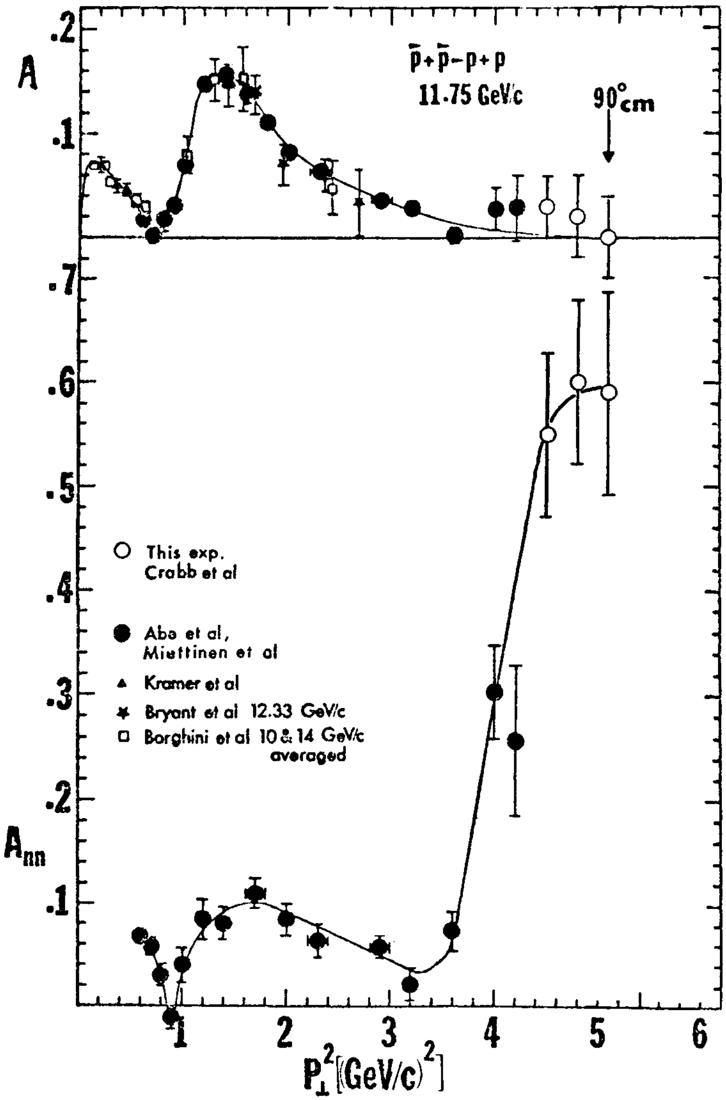

Fig. 7. A and A_{NN} for pp elastic scattering at 11.75 GeV/c

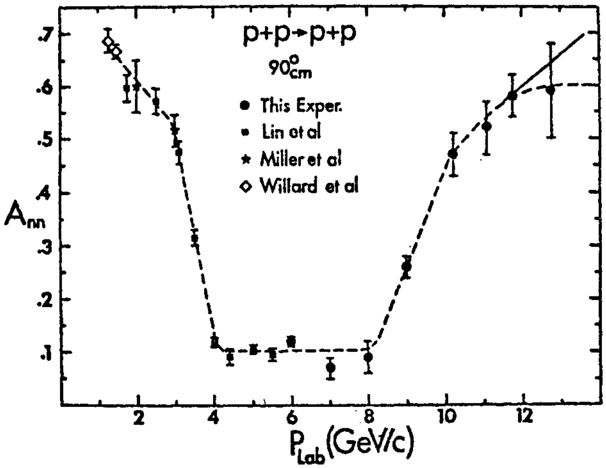

Fig. 8. A_{NN} for pp elastic scattering at 90° cm as a function of incident momentum

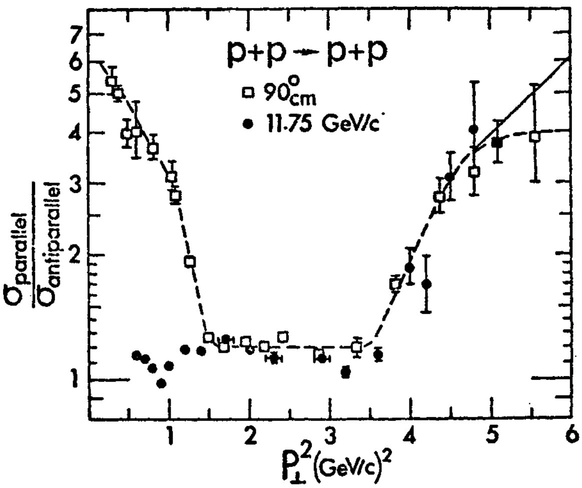

Fig. 9. The cross section ratio $r_{NN} = \frac{\sigma_{parallel}}{\sigma_{antiparallel}}$ of the fixed angle (90° cm) and fixed incident momentum (11.75 GeV/c) plotted against the equivalent $P_{\perp}^{2}$

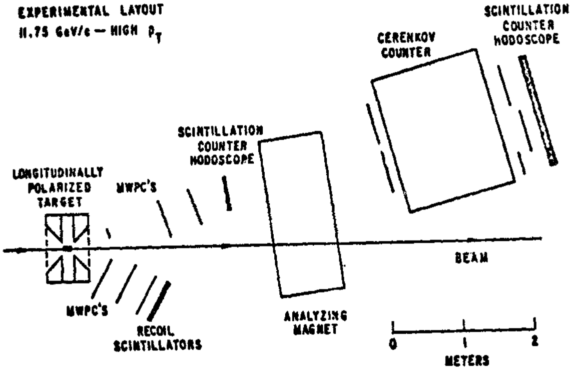

Fig. 10. Layout of the A_{LL} experiment[13]

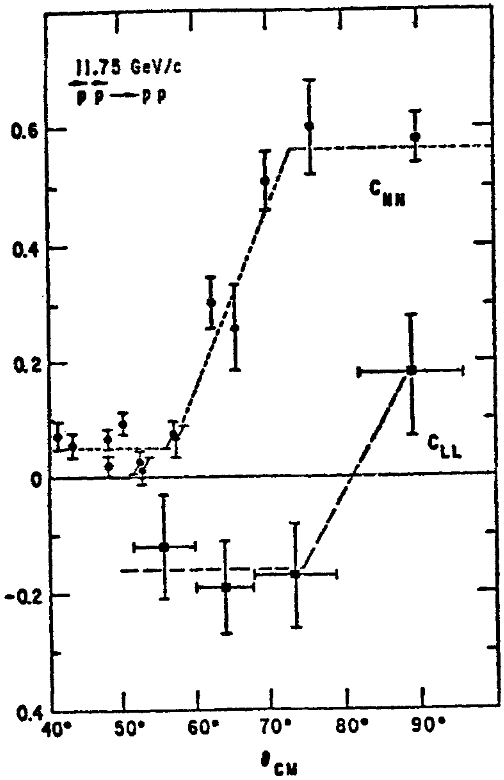

Fig. 11. A_{LL} for pp elastic scattering plotted against cm scattering angle. The A_{NN} data is shown for comparison.

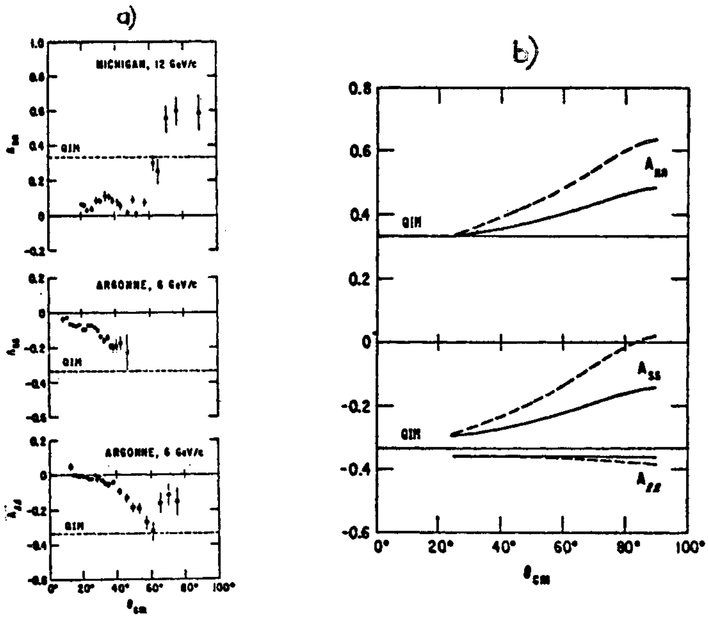

Fig. 12 a) The simple QIM predictions of Farrar et al.[14]

b) The effects of adding instantons to the simple picture

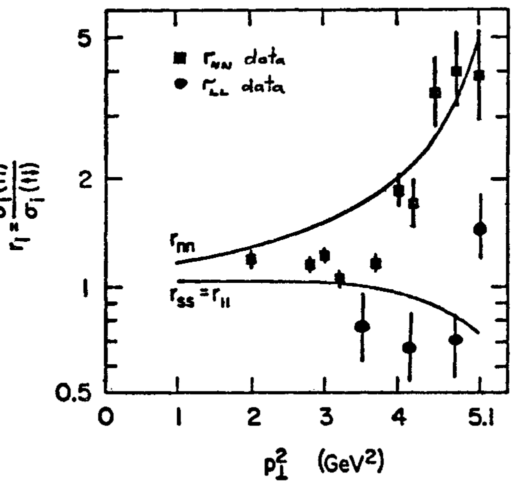

Fig. 13. The QIM predictions of Brodsky et al.[15]
compared with the data

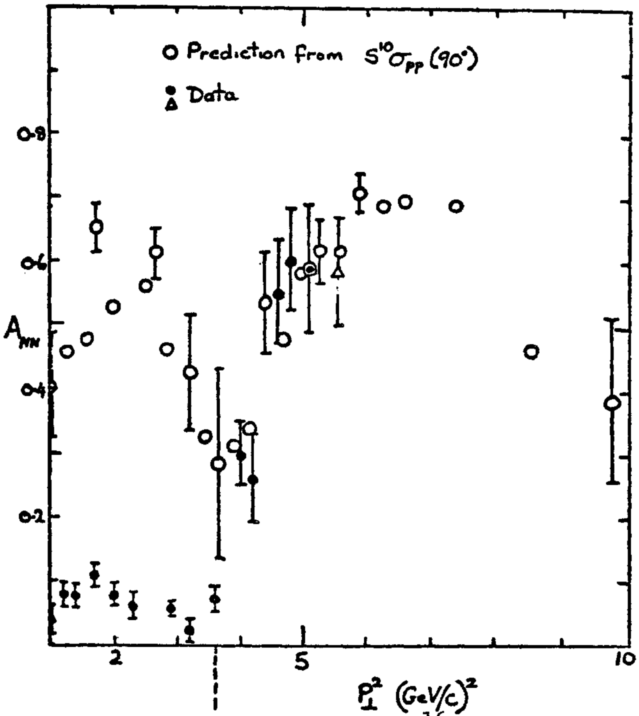

Fig. 14. A prediction of Wolters[16] compared with the data for A_{NN}[9] showing that QIM might be valid above $P_\perp^2 \sim 4(\text{GeV}/c)^2$

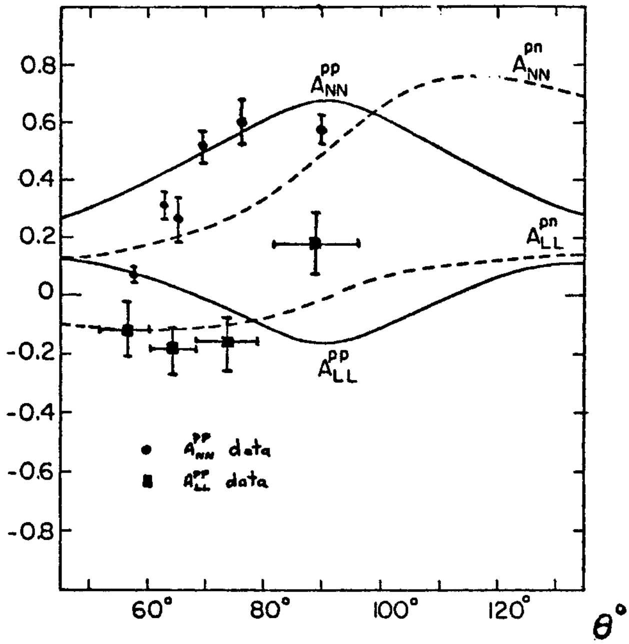

Fig. 15. Spin parameter predictions of the massive quark model of Preparata and Soffer[17] compared with the data

DISCUSSION

BIEDENHARN: There are two comments I would like to make concerning the very nice results presented by Dr. Crabb in his talk. The first concerns the relation he noted between changes in slope of the differential cross section (vs t) and the polarization parameters. This kind of diffraction connection is familiar in these conferences as the "derivative rule" and has been discussed by Miller (p. 410, 2nd Conf.) and by Darden and Haeberli (p. 224, 4th Conf.).

The second remark concerns the theoretical calculations of the coefficients A_{nn}, ..., by the QCD theorists (Farrar, Brodsky, ...). Although the verbal justification for the calculations is quite impressively fancy, what is actually calculated in the "quark interchange model" is the crudest sort of overlap between (NR) SU6 wave functions using the (SU4) product operator of spin- and isospin-exchange. The numerical results agree surprisingly well, but the actual calculation is not at all reliable, being effectively both nonrelativistic and highly nonlocal.

LEHAR: Structure in the parameter C_{NN} can be observed also at lower energies ($\sim$ 140 MeV). The energy dependence of the C_{NN} was plotted by Hess (University of Geneva), and we can see the $C_{NN} \simeq 1$ at 140 MeV.

KLOET: You showed very nice data for np scattering, while the experiment that is really done is dp scattering. How are these np data obtained given the dp data?

CRABB: By using the nucleons in the deuteron for np and pp scattering; one nucleon in the deuteron scatters from the target proton while the other continues on relatively unaffected by the interaction.