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Polarized Protons at the AGS and High-\(P_T^2\) Spin Experiments

A.D. Krisch

Randall Lab. of Physics, The University of Michigan, Ann Arbor, Michigan 48109, U.S.A.

Résumé - Je discuterai les éléments importants qui ont permis d'obtenir des protons polarisés à l'AGS. Ceux-ci nous permettront d'obtenir de nouvelles informations sur le sujet passionnant des forces spin-spin à grand \(P_T\) dans la diffusion élastique proton-proton.

Abstract - I will discuss the major items which were necessary to obtain polarized protons at the AGS. These will allow us to reach new information on the exciting subject of spin-spin forces in high-\(P_T^2\) proton-proton elastic scattering.

When you study proton-proton elastic scattering with an unpolarized beam and an unpolarized target, you can only measure the spin-averaged differential cross-section, \(<d\sigma/dt>\). However if you are able to define and measure the spin of either the target or the beam proton then you can measure spin-orbit effects. If both the beam and the target are polarized then you can also measure spin-spin effects. Measuring the different spin cross-sections might give a great deal of information which is totally inaccessible to spin-averaged measurements with unpolarized beams and targets.

It is necessary to define the direction along which one measures the spin of the protons. We will generally use the normal or \(n\) direction, which is defined to be normal or transverse to the scattering plane. Since in most experiments the scattering plane is horizontal, we will denote the two possible spin directions by up (+) and down (-). Cross-sections with the spins measured along this transverse direction are often called transversity cross-sections, while when the spins are measured along the direction of the momenta, they are called helicity cross-sections. Since there are 2 incoming and 2 outgoing protons in the scattering process and each of these 4 protons can be in either of 2 different spin states, there are \(2^4 = 16\) different pure-spin cross-sections. There are symmetry constraints due to Parity, Time reversal, and Rotational invariance which reduce this number to 5 independent spin cross-sections. Note that the spin-averaged cross-section is simply given by

\[
<d\sigma/dt> = \frac{1}{4} \sum d\sigma/dt(B,T,S,R)
\]

where \(B, T, S,\) and \(R\) refers to the spin states of the beam, target, scattered, and recoil protons. One sums over the final state spins and averages over the initial state spins, giving the factor \(1/4\).

Experiments studying spin effects require three major items of experimental hardware:

1. Polarized Proton Beam
2. Polarized Proton Target
3. Spectrometer to select and detect events.

I will discuss this hardware in some detail because polarized beams and targets are so important to our field of spin physics. For completeness I will also define the spin polarization of a sample of particles, which is

\[
p = \frac{N(+) - N(\bar{+})}{N(+) + N(\bar{+})}
\]
where \( N(\uparrow) \) and \( N(\downarrow) \) are respectively the number of particles with their spins up (\( \uparrow \)) and down (\( \downarrow \)). This definition applies to both the beam polarization and the target polarization.

I will now ask why we should care about spin. Why should we undergo the considerable technical difficulty of constructing a polarized beam and a polarized target to measure pure-spin cross-sections? The simple answer is that pure-spin cross-sections are the fundamental quantities which must be studied to understand the interactions of elementary particles. This now seems quite clear but somehow the importance of spin in high energy scattering was not recognized until the early 1970's. Many physicists believed that "obviously spin becomes unimportant at high energies."\(^1\)

We now know that this unfounded belief is just not true. In the 1970's large and totally unexpected spin-spin forces were discovered at the ZGS in large \( p+p+p+p \) and in \( \sigma_{TOT} \); and large polarizations were discovered in inclusive processes at the AGS, the ZGS, Fermilab and CERN.

Let me give a brief discussion of the history of our program, which was certainly affected by the unfortunate shutdown of the ZGS in 1979. By 1977 it was already clear that the ZGS would be shut down so we organized the Ann Arbor Workshop\(^2\) on Higher Energy Polarized Proton Beams where we considered the possibility of accelerating polarized protons in the Brookhaven AGS and the CERN PS. It soon became clear that there was more support at Brookhaven; and there was a 1978 Brookhaven Summer Study which resulted in a Design Study for Polarized Protons in the AGS.\(^3\) In late 1979 an agreement was reached on funding the AGS polarized beam conversion as an Accelerator Improvement Project with collaborators at Argonne, Brookhaven, Michigan, Rice, and Yale.

Our plan is to have 26 GeV polarized protons with about 60% polarization, and an intensity of about \( 3 \times 10^{10} \) per pulse.\(^4\)

To give the Brookhaven AGS synchrotron a polarized proton capability required several major hardware items:

1. Polarized Proton Ion Source
2. An RFQ to replace the Cockcroft-Walton
3. A low energy transport line to couple the PPIS and RFQ to the LINAC
4. Special Magnets to deal with Depolarizing Resonances
5. Three Polarimeters to measure the Beam Polarization.

The polarimeters work by measuring the scattering to the left, \( L \), and the scattering to the right, \( R \), when the polarized beam scatters from some target such as a thin carbon target. The beam polarization is then given by the ratio of the measured asymmetry, \( A_m \), to the analyzing power, \( A \),

\[
P_B = \frac{A_m}{A} = \frac{1}{A} \left( \frac{L - R}{L + R} \right) \tag{3}\]

The analyzing power is the left-right scattering asymmetry due to strong interactions; and for a 100% polarized beam, the measured asymmetry is equal to \( A \). To accelerate polarized protons in a circular accelerator it is necessary to pass through some very strong depolarizing resonances. Thus I will discuss in some detail how we dealt with the various depolarizing resonances at the AGS.

The first figure shows a layout of the AGS emphasizing those areas where modifications were made to allow acceleration of polarized protons. Note that the polarized \( H^- \) ion source is not in a Cockcroft-Walton dome at 750,000 V; instead the first stage of acceleration is provided by an RFQ at ground potential. This makes control, readback and maintenance of the very complex polarized ion source much easier. RFQ's are quite new devices and ours is one of the first. The 750 KeV polarized \( H^- \) ions emerging from the RFQ are fed by the new low energy beam trans-
port line with two 60° bends into the LINAC. No changes were necessary in the LINAC which accelerates the polarized H⁻ ions to 200 MeV. The 200 MeV polarized protons in the H⁻ ions then scatter from a thin carbon target in the 200 MeV polarimeter which continuously monitors the beam polarization.

The 200 MeV polarized H⁻ ions are then injected into the main synchrotron using the standard H⁻ stripping technique.

In the main synchrotron the polarized protons are accelerated from 200 MeV to 16.5 GeV by passing about 100,000 times through the RF accelerating cavities while circling the ring. Serious depolarizing resonances are encountered during this 1/4 second acceleration process, and special hardware items are required to pass through these resonances without total depolarization. Correction dipole magnets are required to pass through the imperfection depolarizing resonances which are caused by imperfections in the synchrotron's magnetic field. The AGS was constructed with 96 small correction dipole magnets; these can each provide correction fields of a few Gauss over a few inches. These magnets are quite appropriate for producing the harmonics to correct the imperfection resonances, when coupled to 96 new computer controlled power supplies with millisecond rise times.

To jump through the intrinsic resonances requires special pulsed quadrupole magnets with 1 to 2 usec rise times. As shown in Figure 1, one quadrupole was installed in each of the AGS's 12 superperiods. I will discuss these quadrupoles and their rather formidable power supplies in some detail, since jumping the intrinsic depolarizing resonances in the strong focusing AGS is a major problem. So far only 8 of the quadrupoles have power supplies.

You can also see the internal polarimeter which is used to measure the beam polarization during the acceleration cycle in the main synchrotron. The protons scatter from a thin strand of nylon which is briefly flipped into the beam, while scintillation counter telescopes measure the left-right scattering asymmetry. The beam is finally extracted and scatters in the high energy polarimeter which measures the left-right asymmetry in p-p elastic scattering. This polarimeter is a fair sized high energy physics experiment with a liquid hydrogen target, 10 magnets for momentum analysis and scintillation counters. This polarimeter is rather slow but gives an absolute calibration of the beam polarization. The internal polarimeter is much faster but is uncalibrated and thus it must be calibrated against the high energy polarimeter.

The high energy and internal polarimeters were built by Michigan. The 200 MeV polarimeter was built by Rice. The polarized ion source was built by Argonne, Brookhaven, and Yale with a little help from Michigan and Wisconsin. Michigan built the pulsed quadrupoles and Brookhaven built all the other hardware items such as the pulsed quad power supplies, the dipole power supplies, the RFQ, the low energy beam transport line, and the diagnostics and controls.
Figure 2 is a diagram of the ground state polarized proton ion source, which was used at the ZGS, and is similar to the AGS source except for the final ionization stage. The polarized protons start in the gas bottle as $H_2$ molecules which pass through the dissociator where low level RF power dissociates them into hydrogen atoms. The hydrogen then emerges as an atomic beam.

Each hydrogen atom contains an electron and a proton which both have spin and both are totally unpolarized. The atoms then enter a sextapole magnet, which has a very non-uniform field and thus causes the Stern-Gerlach effect. This focuses the electron-spin-up atoms, but defocuses the atoms with the electron spin down. Thus these spin-down atoms are removed from the beam while the electron-spin-up atoms pass through the sextapole. The emerging beam of hydrogen atoms then has its electrons totally polarized and its protons totally unpolarized. The atoms are selected according to electron spin because the electron's magnetic moment $\mu_e$ is about 660 times larger than $\mu_p$; thus the spin of the proton is essentially unaffected by the Stern-Gerlach force.

The atomic beam then passes into an RF transition stage that induces hyperfine transitions, which flip the spins of those atoms with antiparallel electron and proton spins. Those atoms with parallel spins are unaffected because of the narrow frequency band width. Thus after the RF transition stage, the beam of hydrogen atoms has its protons polarized and its electrons totally unpolarized. The atoms then pass into an ionizer where there is an electron plasma which strips the electrons from the atoms by collisions.

A major change was made when the source was transferred from the ZGS to the AGS. It was modified into a polarized $H^-$ source rather than a polarized proton ($H^+$) source, because in the strong focusing AGS one can have many more turns of injection into the main ring with $H^-$ injection than with $H^+$ injection. This increased injection time is particularly important because of the low intensity of polarized ion sources. Thus the electron ionizer was replaced with a Cesium charge exchange device which produces polarized $H^-$ ions. The Brookhaven ion source group has attained 25 $\mu$A of polarized $H^-$. I believe that this is a new world record for polarized $H^-$ from an atomic beam source.

The polarized $H^-$ ions are accelerated to 750 KeV by a Radio Frequency Quadrupole, RFQ, which allows the ion source to be at ground voltage rather than in the 750,000 V Cockcroft Walton dome. This RFQ is shown in Fig. 3. We are very pleased by the stable and reliable operation of the RFQ. It had no significant failures during our 6 week run. I believe that this is the first RFQ ever coupled to an operating accelerator, but I think that within a few years many Cockcroft-Waltons will be replaced by RFQs.
Figure 4 shows the 200 MeV polarimeter which was placed at the end of the 200 MeV LINAC. The polarized protons scattered from a thin carbon target about the size of a pencil lead. Two telescopes of thin scintillation counters detected p-Carbon elastic scattering to the left and to the right. Time of flight and range determination using thin teflon sheets were both employed to determine that the events were elastic. Thus there was a clean signal of elastic p-Carbon scattering events at 12° where the analyzing power, A, is about 83%. The target continuously intercepted about 1% of the LINAC beam and gave a few hundred events in each AGS pulse. Thus in just a few pulses we could get a good measurement of beam polarization just before injection into the main ring. This polarimeter was constructed by Rice with help from Los Alamos, and tested with the Indiana cyclotron polarized beam.

I have several times claimed that depolarizing resonances can cause problems. Some evidence for this claim came from the ZGS, where if no steps were taken to correct the various depolarizing resonances one lost essentially all polarization by 6 or 8 GeV/c. At the strong focusing AGS, the depolarizing resonances are about 10 times stronger so that the polarization disappears even more quickly.

I will now try to explain something of the nature of depolarizing resonances. Recall that the basic principle of a synchrotron is that particles are accelerated by circling the main ring and thus passing repeatedly through the RF accelerating cavity where they are accelerated to tens of GeV in perhaps 200,000 passes through the cavity. To keep the charged particles moving in a circle of radius R requires a vertical magnetic field, B, which gives a force $e\mathbf{v} \times \mathbf{B}$ pointing towards the center of the ring. This force provides the radial acceleration $a = v^2/R$. Unfortunately strong B-fields can depolarize a beam of particles with spin; if the B-field is perpendicular to the axis of spin it can flip the spin.

Fortunately we can inject polarized protons into a synchrotron with their spins vertical and thus parallel to the strong vertical magnetic field. The spins then only precess about their axis and do not flip. However, any horizontal field can cause depolarization of a vertically polarized beam.

Unfortunately we cannot have a synchrotron totally free of horizontal fields. There are two sources of horizontal fields. One is the imperfection fields which can be due to either misalignments in some ring magnets or local problems such as a nick in a magnet pole face. Such imperfect horizontal fields can cause a type of depolarizing resonance which is called an "imperfection" resonance. The second type of depolarizing resonance, which is called an "intrinsic" resonance, is due to the intrinsic horizontal fields which provide the vertical focusing in the synchrotron. This focusing is absolutely necessary to keep the beam within the small aperture of the vacuum chamber, since during a typical one second acceleration cycle the
particles move about 186,000 miles. The beam would have to be aligned to a precision of a few cm in 186,000 miles to avoid the need for these focusing fields. The horizontal focusing fields make the particles oscillate about the central axis of the synchrotron in waves called vertical betatron oscillations.

These horizontal focusing fields can cause significant depolarization.

Fortunately the depolarization caused by these horizontal fields is not always too serious, because the fields may be out of phase with the spin motion. To understand this, notice that there are two frequencies involved. One is the frequency with which the particle sees horizontal fields which we will call \( \omega_h \). For an imperfection field this is simply equal to the cyclotron frequency, \( \omega_c \), at which the particle circles the synchrotron. The second frequency is \( \omega_p \) which is the precession frequency of the particle's spin. This is almost equal to the Larmor precessional frequency except that you must add the Thomas precessional frequency because the circular orbit of the particles is a non-inertial frame. If these two frequencies are out of phase, then the depolarizing effects occurring in subsequent turns around the ring do not add coherently and indeed tend to cancel each other. However, whenever \( \omega_h \) and \( \omega_p \) become equal to integer multiples of each other then the depolarizations on successive turns do add coherently and the beam can be totally depolarized in just 5 or 10 turns, which is about 10 or 20 \( \mu \)sec at the AGS. The intrinsic resonances occur whenever

\[
G_{\gamma} = kP \pm \nu_y
\]

(4)

where \( G \) is \((g-2)/2\) which is 1.79 for a proton, \( \gamma \) is \( E/m \), and \( k \) is any integer, while \( P \) is the periodicity, which is 12 since the AGS has 12 identical superperiods of 20 magnets each. The quantity \( \nu_y \) is the vertical tune, which is the number of vertical betatron oscillations a particle make in one turn around the synchrotron; \( \nu_y \) is about 8.7 for the strong focusing AGS while it was about 0.8 for the weak focusing ZGS. The imperfection resonances occur whenever

\[
G_{\gamma} = n
\]

(5)

where \( n \) is any integer. There are many imperfection resonances, but they are normally much weaker than the intrinsic resonances.

We jump through the intrinsic resonances using the pulsed quadrupole magnets, which rapidly shift the tune value just as each resonance is crossed. Recall that the tune value, \( \nu_y \), is the number of vertical betatron oscillations which a proton makes in one turn around the accelerator; thus \( \nu_y \) is a measure of the focal length of the beam. A quadrupole is a magnetic lens and thus the pulsed quadrupoles rapidly shift the focal length and hence the tune. This tune shift should occur in a time comparable to one turn around the AGS, which is about 2.5 \( \mu \)sec.

The imperfection resonances are passed by using small horizontal fields which exactly compensate the imperfection fields. These fields are really quite weak and an \( /B.dl \) of a few Gauss-inches changes the polarization significantly in the AGS, which is a 1/2 mile circumference ring of 20 KGauss magnets. Thus spin allows an enormously sensitive calibration of the energy of an accelerator.

The estimated strength of the depolarizing resonances at the AGS is plotted against beam momentum in Figure 5.6 The upper dashed line denotes 99% spin-flip while the lower line denotes 1% depolarization. The triangles show the intrinsic depolarizing resonances, which are quite strong, and the circles are the imperfection resonances, which are generally weaker. Notice the very strong intrinsic resonance at 27 GeV/c; we will not be able to jump this using our pulsed quadrupoles so that 26 GeV/c is our planned maximum momentum. However, the spin-flip technique first discovered accidentally at the ZGS and now used successfully at Saclay may allow us to pass this very strong resonance. Spin flip
is the technique of allowing a very strong resonance to exactly reverse the polarization by making it even stronger. This spin flip of exactly 180° is an interesting quantum mechanical effect which indeed seems to work; while classically the spin would precess again and again as the resonance becomes stronger.

![Figure 5. Depolarizing Resonance at AGS](image)

The technique of using pulsed quadrupoles to jump through an intrinsic depolarizing resonance is demonstrated in Figure 6 where the vertical tune, \( v_y \), is plotted against the time in the acceleration cycle. Normally the tune has a constant value, which is independent of time; it is about 8.7 at the AGS. The sloping line is the curve \( G_y = kP \pm \nu \), which gives the \( \nu \) at which the resonance occurs for each \( y \). Of course, \( \gamma \) is proportional to the time in the acceleration cycle. The resonance band has some width because of the broadening of the beam due to synchrotron oscillations. When the resonance band crosses the fixed tune value, this width causes the beam to be in the resonance condition for a fairly long time, \( \Delta t \). This time might be hundreds of \( \mu \)sec and I mentioned earlier that 10 or 20 \( \mu \)sec is long enough to totally depolarize the beam. Thus passing through a depolarizing resonance under normal conditions with \( \nu \) constant can rapidly depolarize the beam.

![Figure 6. Vertical Tune](image)

To avoid depolarization we use the pulsed quadrupoles to rapidly shift the tune as shown in the right-hand curve. Note that the tune is then returned to its normal value in a few milliseconds along a curve parallel to the resonance curve. Notice that if the rise time of the pulse is about 2 \( \mu \)sec, then the beam spends less than 1/2 \( \mu \)sec in the resonance condition, which is not long enough for coherent polarization to build up. Thus by properly using the pulsed quadrupoles we can jump through the intrinsic depolarizing resonances without significant depolarization.

![Figure 7. Diagram of Pulsed Quadrupole](image)
Figure 7 is a diagram of one of the 12 pulsed quadrupoles magnets which we designed to put inside the AGS. Good quadrupoles must have hyperbolic pole tips, as shown. The magnets are each 19 cm wide by 16 cm high by 50 cm long. It is impossible to obtain a few μsec risetime with iron core magnets. With thin iron lami­nation cores you can reach about 10 μsec, as we did at the ZGS. But to reach μsec risetimes, magnets must be made of ferrite. Dipoles, such as fast kicker magnets have been built of ferrite, but I believe that ours are the first ferrite quadrupoles.

There are several problems about constructing magnets of ferrite. The first is that ferrite is very expensive; it costs about $50 per pound. The second problem is that ferrite is very hard. It is considerably harder than steel; thus it cannot be machined with normal tools. The third problem is that the ferrite must be machined to a precise hyperbolic surface. The final problem is that ferrite is very fragile; if you allow it to slightly heat-up during machining, it shatters. We experimentally determined that this shattering does occur.

We solved these various problems in different ways. When the ZGS was closed-down, we obtained the ZGS's RF acceleration cavity which contained 1.7 tons of ferrite at zero cost.

We machined the ferrite on a new computer-controlled milling machine, which we induced our University to buy. This computer-controlled machine allowed us to cut the hyperbolic pole faces with a precision of a few mils in a short time. To cut the very hard ferrite we used special diamond impregnated tools on the milling machine. The diamond chips ground the ferrite into the hyperbolic shape. The problem of the ferrite overheating was solved by doing the machining in a bath of water.

We tested the quadrupoles using a power supply which produced about 1500 amps at 15,000 volts which is about 22 Megawatts during the risetime. Fortunately the 8 AGS power supplies each produce this 22 MW for less than 2 microseconds. These 22 MW power supplies are really massive and complex items requiring many ignitron and thyratron tubes. That is why we could only afford 8 of them for this first run. Two more are now being constructed. As shown in Figure 8, we obtained a risetime of 1.6 μsec in going from 10% to 90%, which is certainly acceptable.

Figure 8. Pulse Quad Risetime

Figure 9. Assembled Pulsed Quadrupole

Figure 9 shows a photograph of a fully assembled quadrupole. Notice the long white ceramic vacuum chamber inside the quadrupole. Normally, the vacuum chambers in accelerators are made of thin stainless steel. In our quadrupoles the eddy currents in such stainless steel chambers would increase the risetime to about 4 microseconds, which is unacceptable. To avoid this anticipated problem, we built ceramic vacuum chambers. Bonding the ceramic chambers to the stainless steel flanges required thin strips of monel metal which can be bonded to
the ceramic by heat treatment. This bonding was done by an aerospace company which normally works on rocket nose cones.

I will now briefly discuss the polarimeters. The internal polarimeter target is a thin 4 mil strand of nylon fishing line. This strand must continuously move at several meters per second to avoid being melted by the beam. The scattering from the strand is detected by a left and a right telescope, each containing 3 scintillation counters in coincidence. This polarimeter is quite fast but is uncalibrated since there is little fundamental knowledge of proton-fishline scattering. It must be calibrated against our high energy polarimeter.

![Figure 10. Layout of the High Energy Polarimeter and our AGS Experiment](image)

Figure 10 shows the layout of our AGS experiment on spin effects in large-$P_z^2$ proton-proton elastic scattering. It also shows the high-energy polarimeter on the left, which contains a liquid hydrogen target, and measures the p-p elastic scattering events to the left, $L$, and the scattering events to the right, $R$. We then use the measured left-right asymmetry, $(L-R)/(L+R)$, to obtain the beam polarization, $P_B$, from the equation

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

where $A$ is the p-p analyzing power at the appropriate energy and angle. The analyzing power was measured in a CERN experiment using a polarized proton target and an unpolarized beam.

The polarized beam then continues and hits the polarized proton target (PPT); we measured the resulting p-p elastic scattering events. There are 6 magnets for momentum analysis, and a sixfold eight-channel scintillation counter hodoscope for detecting the elastic events. The experiment simply involves measuring the p-p elastic scattering cross-section in the four spin states: beam up, target up ($++$); beam up, target down ($+\!\!-$); beam down, target up ($-\!\!+$); and beam down, target down ($--$). The target spin can be conveniently reversed every few hours since it takes about 30 mins to reverse the polarization. The beam polarization was flipped every 2.4 sec pulse. This spin flipping is very beneficial, because flipping the beam spin on each pulse gives great resistance to most systematic errors.

I will now briefly discuss polarized proton targets. Figure 11 is a schematic diagram of our polarized proton target (PPT).

![Figure 11. Polarized Proton Target](image)
The target contains a magnet with specially shaped pole tips which produce a highly uniform 25 kilo-gauss magnetic field. A canister containing polarized target beads is placed inside this field. This canister is held at a very low temperature of about 0.5°K. The spin polarization of the particles in the target is caused by the population difference of the different spin states. This polarization is given by the equation

$$p_T = \tanh \left( \frac{\mu B}{kT} \right)$$

(7)

The quantity B is the magnetic field while μ is the particle's magnetic moment, k is Boltzmann's constant and T is the temperature. Notice that, if the field is 25 kG and the temperature is 0.5°K, then when the proton's magnetic moment, $\mu_p$, is substituted into the equation, the polarization is only about 1/3%. This technique is called the brute force technique of polarization and it clearly does not work very well.

This unfortunate problem was overcome in the late 1950's when two very clever atomic physicists, Professor Abragam at the College de France, and Professor Jeffries at Berkeley, came up with an idea called dynamic nuclear polarization. With this technique one polarizes some free electrons and then transfers their polarization to nearby protons. As before, the magnetic moment of the electron is 660 times larger than $\mu_p$. Thus the electron is much easier to polarize and with $T = 0.5°K$ and $B = 25$ kG, $99.7\%$ of the electrons become polarized. Then spin transitions can be induced in temporary polarized-electron/unpolarized-proton states by pouring in microwave power at a specific frequency of about 70 GHz. In our target these microwaves are produced by a carcinotron tube. The polarization of the protons is then monitored with a NMR system operating at 107 MHz. It should be noted that the ratio of 70 GHz to 107 MHZ is 660 which is exactly the ratio $\mu_e:\mu_p$, as it should be.

It is necessary to provide a great deal of cooling to maintain the polarized target at 0.5°K. With our high beam intensity more than 100 mW is needed at 0.5°K, which is quite difficult. The basic cooling is provided by liquid $^4$He at 4°K. We use about 200 liters/day of this liquid $^4$He. The $^4$He is then cooled to about 2°K by pumping, and it in turn cools the $^3$He cryostat so that the incoming $^3$He gas is cooled and liquefied at about 2.5°K. The $^3$He is then pumped very hard with large roots blower pumps to cool it to 0.5°K.

The magnet of the polarized proton target must have a field uniform to better than 1 part in 10⁴. Special pole tips and a specially stabilized power supply provide this highly uniform and stable field. Also the microwave power must have a very narrow band width to insure that we induce one hyperfine transition but not the other transition, which would depolarize the protons. To avoid radiation damage problems we now use radiation-doped NH₃ target beads irradiated at the Brookhaven Synchrotron Light Source. We also use a $^3$He/$^4$He mixture in the $^3$He cryostat to obtain better local cooling of the beads, since $^4$He is a superfluid at 0.5°K.

Let me finally show some high energy physics cross-section data to prove that I am really a high energy experimenter. Figure 12 is a plot of the differential proton-proton elastic scattering cross-section plotted against my favorite scaled $P_1^2$ variable. This variable, $p_1^2$, is useful because it removes the energy dependence and allows comparison of data at different energies. The black squares are unpolarized data from the CERN ISR, at $s = 2800$ GeV², and the triangles and diamonds are polarized data from the ZGS. The solid triangles indicate spins parallel to one another while the open diamonds are spin-antiparallel cross-sections. Much activity can be noted around the breaks in the cross-sections. The spin dependence is small but quite noticeable at the first break near $P_1^2 = 1$ (GeV/c)²; and then the two cross-sections merge again. A very large and totally unexpected spin-spin effect occurs at $P_1^2 = 3.5$ (GeV/c)² where the 2nd break in da/dt occurs.
The break in $\frac{d\sigma}{dt}$ only seems to occur when the spins are parallel; when the spins are antiparallel there may be no break at all. Thus there appears to be a very tight relationship between spin and this hard scattering component, which from its slope corresponds to a size of $1/3$ Fermi. In other words, this hard scattering rarely occurs unless the spins are parallel. This data is about the maximum $P_{12}$ available at the ZGS since $P_{12} = 5.1$ (GeV/c)$^2$ corresponds to $90^\circ$cm at 11.75 GeV/c. It is obviously interesting to extend the $P_{12}$ range of this data and to see if the $d\sigma/dt$ (+) and $d\sigma/dt$ (+) curves continue to move apart, come back together, or become parallel. This extension requires a higher energy polarized proton beam such as the AGS.

In Figure 13 we have plotted the ratio of the spin-parallel to the spin-antiparallel cross-section against $P_{12}$. This plot shows the spin effects in much more detail by removing the $10^5$ change in the cross-section over our $P_{12}$ range. You can now clearly see the dramatic and abrupt change in the spin-spin forces at $P_{12} = 3.5$ (GeV/c)$^2$ which is the onset of the hard scattering region. This graph includes some additional data at $P_{12} = 4.7$ and 5.1 (GeV/c)$^2$ with smaller errors. We have increased our $90^\circ$cm statistics by a factor of 4, so that this point is now more than 10 standard deviations from zero. We now have a very high confidence level that this huge and unexpected spin-spin effect will not go away and must be confronted by our theoretical colleagues.

When we first saw these effects in 1977, we believed that the large spin-spin forces were clearly a high-$P_{12}$ effect, which therefore directly probed the short range behavior of the proton's constituents. However after two seminars at CERN and Copenhagen, two of our older and wiser colleagues, Weisskopf and Bethe, urged caution. They both pointed out that at our energy the large spin effect only appear near $90^\circ$cm and may be caused by some $90^\circ$cm effects rather than by large-$P_{12}$ effects. After considerable thought we came to understand that there was no theoretical way to answer these concerns. Because of symmetry, $90^\circ$cm is a very special point for p-p scattering and there could indeed be large spin correlations caused by particle identity effects having nothing to do with hard scattering of the constituents. Therefore we decided to try to answer this question experimentally.

The experiment consisted of studying the $P_{12}$ dependence of proton-proton elastic scattering by varying the beam momentum while holding the scattering angle fixed at $90^\circ$cm. In the earlier experiments we had varied $P_{12}$ by varying the
scattering angle with the beam momentum held fixed at 11.75 GeV/c. The data from this 90° cm experiment is shown in Figure 14, where we have plotted the spin-parallel to spin-antiparallel ratio against \( P_{\perp}^2 \) for both the fixed-energy 11.75 GeV/c data and the fixed-angle 90° cm data. Clearly the dramatic onset of the spin-spin effect occurs at exactly the same \( P_{\perp}^2 \) in both experiments. The two sets of data points fall right on top of each other. Thus the spin effects cannot be due to 90° cm particle identity effects and must be due to large-\( P_{\perp}^2 \) hard-scattering effects.

I will next show in Figure 15 the pure initial spin cross-sections themselves \([d\sigma/dt(++)\) and \(d\sigma/dt(++)]\) plotted against \( P_{\perp}^2 \) for 90° cm proton-proton elastic scattering. You can clearly see the onset of the large spin-spin forces at high \( P_{\perp}^2 \) just at the position of the second break in \( d\sigma/dt \). It is very apparent that the large-\( P_{\perp}^2 \) hard-scattering events rarely occur unless the spins are parallel.

The main goal of our program with the Brookhaven AGS polarized proton beam is to extend this curve. Perhaps after a deep dip the \( d\sigma/dt(++) \) curve will become parallel to the \( d\sigma/dt(++) \) curve and lie exactly a factor of 2 below it. Perhaps \( d\sigma/dt(++) \) will go rapidly to zero and bring confusion to everyone. Perhaps something else will happen that no one has thought of; this would continue the recent history of polarization experiments finding totally unexpected effects both at large-\( P_{\perp}^2 \) and in \( \Delta\sigma_{dt} \).11

Figure 15 gives a very clear demonstration of why high intensity and high luminosity are necessary to study high-\( P_{\perp}^2 \) spin effects. The cross-section near \( P_{\perp}^2 = 6 \) (GeV/c)\(^2\) is about \( 10^{-33} \text{ cm}^2/(\text{GeV/c})^2 \). This is a very small cross-section and at larger \( P_{\perp}^2 \) it will be even smaller. We will need high polarized beam intensity to study these cross-sections at the AGS. This will allow probing the fundamental spin-spin forces in the nucleon-nucleon interaction at even shorter range which may allow us to finally understand the constituents of the nucleons and the nature of strong interactions.
I will not have time to discuss in detail the fascinating process of tuning through more than 30 depolarizing resonances which let us reach 16.5 GeV/c with a polarization of about 40%. Let me just note that the intrinsic resonances were about as strong as calculated, but the imperfection resonances were about 10 times stronger and every one had to be corrected. It was a great deal of work. Moreover we discovered a third type of imperfection resonance which is driven by the intrinsic fields of the accelerator. To correct this we had to use the 96 dipoles to produce a 9th harmonic (sin 9q) although the resonance occurred at Gy = 27. Terwilliger and Courant had suggested that such a resonance might exist. The tuning curve for correcting this resonance is shown in Fig. 16. We ran more than 100 such curves for the various resonances.

During the last two weeks of July we obtained the first measurement of An in p + p + p + p at 16.5 GeV/c. The intensity was low and we spent much of this period studying the polarized beam so we were not able to go to the very large P2 region which is so interesting. However we did make one measurement at P2 = 2.2 (GeV/c)2, which is plotted in Fig. 17 against incident momentum along with earlier ZGS data. Within our errors it appears that the spin-spin correlation parameter, An, is independent of incident momentum in this medium P2 region. Note that in this same run we simultaneously measured the Analyzing Power in two independent ways, using the beam polarization (A_B) and the target polarization (A_T). With good precision we found that A_B = A_T indicating that we understand our systematic errors.
showed the layout of our AGS experiment. A high intensity beam of almost $10^{11}$ protons per pulse is extracted from the AGS and scatters from our polarized proton target. We have 2 magnets for momentum analysis in the large-angle recoil arm and 4 magnets in the forward arm. The forward and recoil protons are each detected by an 8-channel 3-fold scintillator hodoscope telescope. The target protons can be polarized in either the up(+) or down(-) spin state, while the beam is unpolarized. Thus we can measure one-spin effects such as $A$, the analyzing power, which is related to the spin-orbit interaction.

In Figure 18 the analyzing power, $A$, is plotted against $P_{L}^2$ for $p+p+p+p$ at 28 GeV/c. This 1982 and 1983 data, which extends out to $P_{L}^2 = 6$ (GeV/c)$^2$, was recently published. Some CERN data at 24 GeV/c is also shown. Notice that the CERN group saw a sharp dip near $P_{L}^2 = 1$ (GeV/c)$^2$, which is the position of the first "break" in $da/dt$. They also reported a very deep dip near $P_{L}^2 = 3.5$ (GeV/c)$^2$, which is exactly where our ZGS data showed the dramatic rise in spin-spin effects. They stressed the possible relation between the deep dip in $A$ and the sharp rise in $A_{uu}$. Our AGS data confirmed the dip near $P_{L}^2 = 1$ (GeV/c)$^2$ and the broad peak centered near $P_{L}^2 = 2$ (GeV/c)$^2$. By improving our polarized target's cooling power to about 120 mW and switching to "radiation resistant" NH$_3$ PPT beads, which were "radiation doped", we were able to run with a beam intensity of about 7 $10^{10}$ protons per pulse. We thus obtained data on $A$ up to $P_{L}^2$ of 5.95 (GeV/c)$^2$ with fairly good precision. The dip reported by the CERN group certainly exists, but it appears not nearly so deep as suggested by their larger error data.

Finally consider the behavior near $P_{L}^2 = 6$ (GeV/c)$^2$. This first data on spin-orbit effects in the large-$P_{L}^2$ hard-scattering region beyond $P_{L}^2 = 4$ (GeV/c)$^2$ suggested that $A$ may be large and possibly rising in this high-$P_{L}^2$ region. We were very eager to take more data near $P_{L}^2 = 6$ (GeV/c)$^2$. In Spring 1984 we did improve our statistics at $P_{L}^2 = 5.95$ (GeV/c)$^2$ and measure another point at $P_{L}^2 = 6.56$ (GeV/c)$^2$. The rather surprising new data is shown in Fig. 19. I have no idea what this rising $A$ at high $P_{L}^2$ might mean. No one has ever before looked at such high-$P_{L}^2$ spin effects; and this sharp rise is quite unexpected. Most QCD models predict that $A = 0$ at high-$P_{L}^2$. Perhaps this strange result is a continuation of the historical trend that, whenever spin effects are studied in an unexplored region, there are surprises.

Note that much of the interest in the large-$P_{L}^2$ spin-spin data is due to the problem which this data causes for the conventional quark model of the proton. The spin-$1/2$ proton is assumed to contain three spin-$1/2$ quarks which must be in the ground state to give the very successful spectroscopy results of the quark model. Thus when two protons scatter, each must have two quark spins parallel to the proton's spin and one quark spin.
antiparallel. Some simple counting$^{15}$ of the nine quark-quark spin cross-sections shows that, if the quarks scatter independently, it is impossible to get a $d\sigma/dt(++):d\sigma/dt(++)$ ratio of 4 for p-p scattering, which is what we found. If the quarks interfere with each other, then one can obtain any ratio; but quark independence is an important assumption needed for the successes in spectroscopy.

Many theoretical papers$^{16-25}$ have been written to discuss the problem caused by this large and unexpected spin-spin effect. I believe that this difficulty cannot be eliminated in any simple way except to say that QCD and the quark model will only work at much larger $P^2$. Unfortunately there is no spin data and very little other scattering data at larger $P^2$. I believe that the ZGS spin-spin data and our new one-spin AGS data suggests that something is occurring which can not be understood in terms of the conventional quark model. This is not surprising to me because the quark model and QCD were established long before any data on spin effects at high-$P^2$ were available. Since physics is an experimental science one should not be surprised to find difficulties with theories formulated before new experimental regions were explored.

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