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Elastic Spin Experiments at UNK, Fermilab, and SSC*

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I will discuss experiments which measure the spin forces in high- $P_\perp^2$ proton-proton elastic collisions. Our speciality is studying the effects of spin on the proton's inner structure by using polarized proton beams and polarized proton targets. If neither the beam nor the target is polarized then one can only measure the elastic differential cross-section. If either the beam or the target is polarized then one can measure one-spin quantities such as the left-right asymmetry, A, which is related to the spin-orbit force. If both the beam and the target are polarized, then one can measure the spin-spin force.

Fig. 1 shows some data[1] from the late 1970's taken using the Argonne ZGS polarized proton beam; the differential elastic proton-proton cross-section is plotted against a scaled $P_\perp^2$ variable. There are three different sets of data: unpolarized s = 2800 GeV^2 data from the ISR; some 12 GeV ZGS data with the spins parallel; and some with the spins anti-parallel. In the small angle diffraction peak all three sets of data fall exactly on top of each other when plotted against this scaled $P_\perp^2$ variable. Apparently in the diffraction peak, where the protons just have glancing interactions with the outside of each other, neither the spin nor the energy are very important. Fourier transforming the $e^{-10P_\perp^2}$ fit shows that the outer size of the proton is about 1 Fermi.

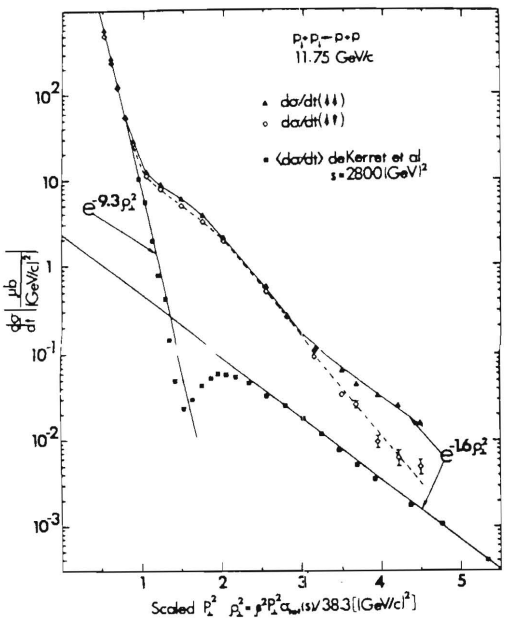

Fig. 1 Spin-spin effects in large-$P_\perp^2$ p-p elastic scattering.

At larger $P_\perp^2$ the unpolarized data clearly has a different slope after the sharp dip; Fourier transforming this $e^{-1.5P_\perp^2}$ hard-scattering component gives a size of about 0.3 Fermi; this is apparently the size of the protons' constituents when they interact with each other. The SLAC deep inelastic e-p experiment[2], which scattered an electron from a proton, found that the constituents are almost point-like. But, our 1966 unpolarized 90°_{cm} p-p elastic experiment[3] showed that, when two constituents scatter from each other, their characteristic size is about 0.3 Fermi.

The surprising new spin result was that this hard scattering rarely occurs unless the spins are parallel. When the spins are anti-parallel the cross-section just

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continues to drop. In simple language the protons seem to have violent collisions only when they spin in the same direction. This unexpected result disagreed with most models of strong interactions; in 1978 most people believed that spin would become less important in higher energy violent collisions. Instead we found that the spin effects were largest in the most violent collisions. Many theoretical papers have addressed this unexpected result, but there is still no widely accepted explanation.

After seminars about this result, two of our most distinguished colleagues, Professors Bethe and Weisskoff, both made the same comment: "This is very interesting, but your effect is only large near 90°_{cm}; perhaps you are not really looking at a large-$P_\perp^2$ hard-scattering effect, but instead some 90°_{cm} particle identity effect." After some thought, we decided that this question could only be answered experimentally. Therefore we did a second experiment where we varied $P_\perp^2$ by now holding the scattering angle fixed at 90°_{cm} and varying the incident energy[4]. In Fig. 2 we plot the ratio of the spin-parallel to the spin anti-parallel elastic cross-section for both the newer 90°_{cm} fixed-angle data[4] and the 11.75 GeV/c fixed-energy data[1] already shown in Fig. 1. This ratio removes the 10^{-7} drop in the cross-section; thus it more clearly shows the spin effects. The fixed-energy ratio goes up to 4 at large $P_\perp^2$; moreover, the 90°_{cm} fixed-angle ratio increases to 4 at exactly the same $P_\perp^2$ value. Clearly this is not a 90°_{cm} particle-identity effect because the low energy 90°_{cm} points, where the spin effects are small, are just as much at 90°_{cm} as the high energy points, where the spin effects are large. Therefore, it is a large-$P_\perp^2$ hard-scattering spin effect.

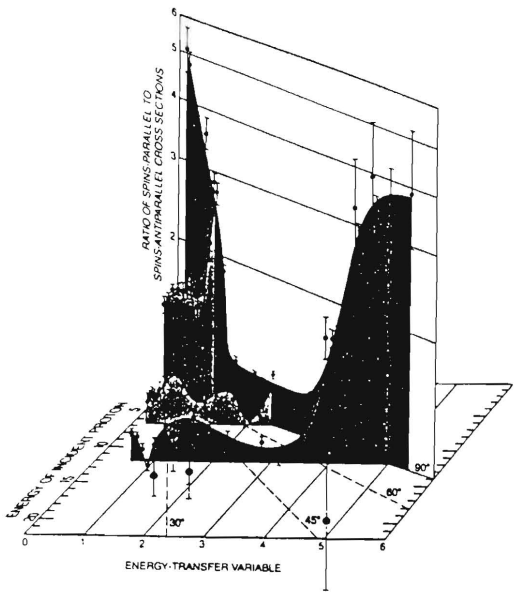

Fig. 2 Three-dimensional plot of pp elastic scattering.

We did not understand this effect; but being experimenters we decided to extend the 90°_{cm} curve to higher energies. Thus we moved to the AGS to accelerate a higher energy polarized proton beam. It was very difficult to accelerate polarized protons to 22 GeV; it required individually overcoming 45 depolarizing resonances which took seven weeks of dedicated AGS beam time. Nick Samios often came to the AGS control room to politely remind me that these studies cost a million dollars a week and to ask when they would end. We did succeed after much hard work, but clearly a new technique was required for significantly higher energies.

Fortunately around 1975 two clever Russians at Novosibirsk, Derbenev and Kondratenko, proposed the Siberian snake concept to simultaneously overcome all depolarizing resonances[5]. To understand a Siberian snake, consider a spinning

proton circling an accelerator ring with its spin initially pointing up at 0°. Next suppose that, in one turn around the ring, the many magnetic imperfections rotate the spin to 5°; then the Siberian snake rotates the spin by 180° to 185°. During the next turn around the ring, the same imperfections now rotate the spin from 185° back to 180°. Finally the Siberian snake again rotates the spin by 180° back to 0° where it started. This clever idea makes the depolarizing effects cancel themselves.

No one tested Siberian snakes until the 1985 Ann Arbor Workshop on Polarized Beams at the SSC[6], which was organized by Ernest Courant, Owen Chamberlain, the late Kent Terwilliger and myself. The Workshop concluded that one could accelerate polarized proton beams at the SSC, but only by using Siberian snakes. Each 20 TeV SSC ring will have about 36,000 depolarizing resonances; overcoming them individually at one shift each would require 12,000 days. The Workshop also recommended that the concept should soon be tested somewhere. The new 500 MeV Indiana Cooler Ring had planned a polarized proton beam and 6 m long straight sections; after approval of our proposal, we built a Siberian snake and installed it there. Our Siberian snake contains a 2 T·m superconducting solenoid magnet which can rotate the spin by 180°; it also contains 8 quadrupoles which do nothing to the spin but compensate for the focusing and orbit rotation caused by this solenoid.

We studied the $G\gamma = 2$ imperfection depolarizing resonance which occurs at 108 MeV; $G = 1.7928$ is the proton's anomalous magnetic moment. The measured polarization[7] at 104 MeV is plotted in Fig. 3 against the imperfection magnetic field which we varied using some solenoid magnets in the Ring. With the snake off there was full polarization only if we exactly corrected these imperfection fields; a very small imperfection $\int B \cdot dl$ destroyed the polarization. But with the snake on, there was full polarization over the entire region. This result showed that the Siberian snake could easily overcome the imperfection depolarizing resonance. We later showed that Siberian snakes can also overcome other depolarizing resonances.

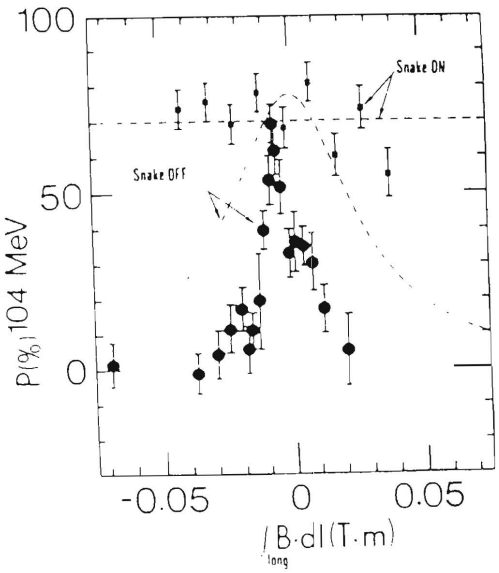

Fig. 3 Siberian snake overcoming $G\gamma = 2$ imperfection depolarizing resonance.

After people started to understand this result, interest began to grow in other laboratories around the world. About five medium energy facilities now plan to install Siberian snakes. We were especially interested in using Siberian snakes at high energy; therefore we formed the SPIN Collaboration which submitted the EOI-001 proposal to SSC. Our Collaboration contains about 40 accelerator physicists, 40 high energy experimenters and one high energy theorist, from Michigan, Indiana, Fermilab, North Carolina, IHEP-Protvino, JINR-Dubna, Moscow State University, INR-Troitsk, Kyoto, and KEK.

After some discussion, the SSC decided to modify th 20 TeV ring lattices to create in each ring about 26 spaces each 20 m long for the possible later installation of Siberian snakes; this is about one kilometer of empty space, as shown in Fig. 4, which also shows the low energy polarized beam hardware. We hope to someday study spin effects in 2 TeV p-p elastic scattering out to $P_\perp^2 = 10\ (\mathrm{GeV}/c)^2$ using a 2 TeV Booster polarized beam and an internal polarized gas jet target.

Fermilab then became interested in possibly installing Siberian snakes in the new 150 GeV Main Injector. The SPIN Collaboration was commissioned by Fermilab to produce a Design Study Report on Acceleration of Polarized Protons in the Main Injector. The 146 page Design Study Report[8] was submitted on 31 March 1992; it includes: schedules, cost estimates, detailed hardware designs, and management responsibilities. The new hardware needed to accelerate a polarized beam at Fermilab is shown in Fig. 5; notice the polarized ion source, the RFQ, the low energy polarimeter, the switching magnet into the main preinjection line and the polarimeter at the end of the LINAC. The 8 GeV Booster has: another polarimeter; two pulsed quadrupoles to overcome the one intrinsic depolarizing resonance; and one partial Siberian snake to overcome about ten imperfection depolarizing resonances. The 150 GeV Main Injector has: 2 Siberian snakes; a fast uncalibrated polarimeter; and a Coulomb-nuclear interference polarimeter which is much slower but is calibrated. The spin rotator in the extraction line corrects the spin rotation during transfer from the Main Injector to the Tevatron, which occurs because spin matrices do not commute. Our SPIN Collaboration is now studying the acceleration and storage of polarized protons in the Tevatron; we hope to do polarized beam experiments with an internal polarized jet target in the Tevatron and a solid polarized target in the 120 GeV extracted beam. We would measure two-spin effects in p-p elastic scattering at both 120 GeV and 1 TeV out to $P_\perp^2$ of about $10\ (\mathrm{GeV}/c)^2$.

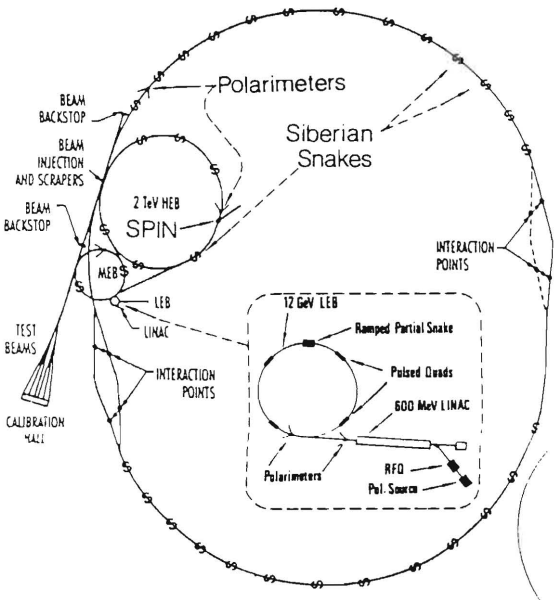

Fig. 4 SSC polarized proton beam.

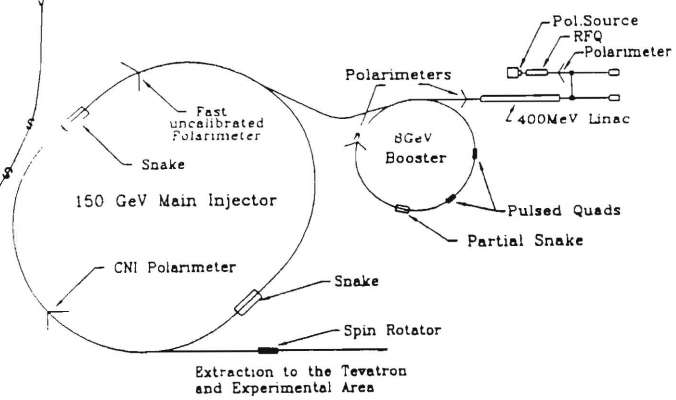

Fig. 5 Fermilab Main Injector polarized proton beam.

While preparing for the AGS polarized beam program, we measured large-$P_\perp^2$ elastic p-p scattering with an extracted high intensity unpolarized 28 GeV proton beam on a solid polarized target. The QCD experts remained mystified by our two-spin effects, but still made a firm prediction that the left-right asymmetry A should go to zero; moreover the prediction should get better at higher energy and at higher $P_\perp^2$. Instead, we found[9] that the left-right asymmetry increased at higher $P_\perp^2$, as shown in Fig. 6. Some people could not believe this and suggested that our data might be wrong. We then built a high cooling power polarized proton target which allowed a beam intensity of 10^{11} s^{-1}; this produced the more precise new 24 GeV data, which verified that spin effects are large at high $P_\perp^2$.

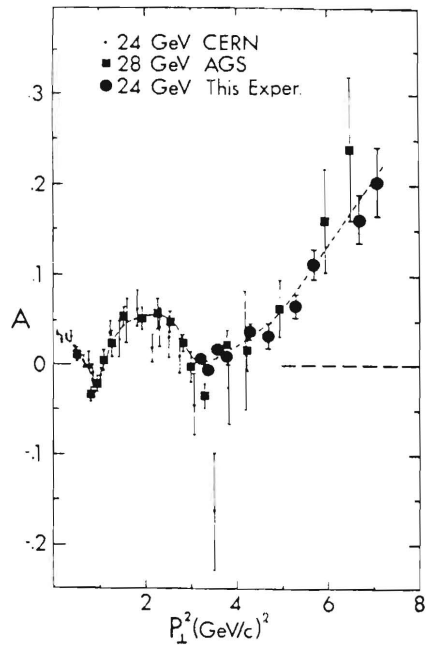

Fig. 6 Plot of A against $P_\perp^2$.

To study even higher energy, we then planned the NEPTUN-A experiment at the new UNK accelerator in Russia. UNK should first operate at 400 GeV in 1995; a 600 GeV extracted beam program should start around 1997. The 3 TeV superconducting UNK-2 should start around the year 2000 in the same tunnel. The 21 km circumference UNK accelerator is shown in Fig. 7 along with the town of Protvino, and the existing 70 GeV accelerator U-70, which will be the injector for UNK. The city of Serpukhov is just past UNK. Our NEPTUN-A experiment will be in the SS-3 straight section about 11 km from Protvino. The beam transfer line from the 70 GeV U-70 accelerator into the UNK 400 GeV main ring was recently finished. This 2.6 km long transfer line should be tested soon; it uses standard UNK 6 m long warm dipoles and 3 m long warm quadrupoles.

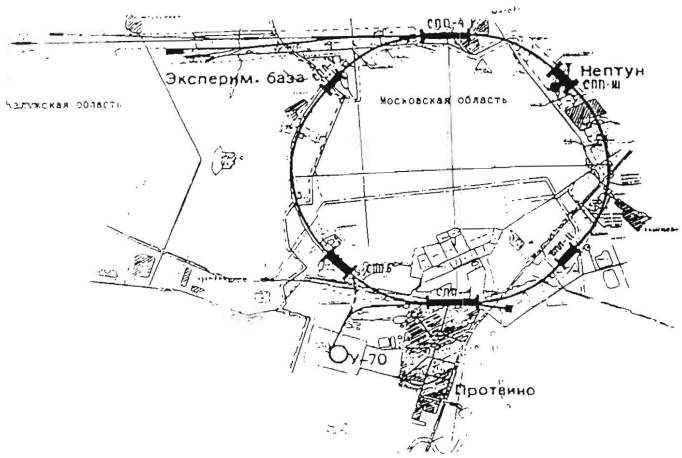

Fig. 7 UNK, U-70 and Protvino.

We should start taking large-$P_\perp^2$ elastic p-p data at 400 GeV during late 1995; Solovianov is our chief Russian collaborator and the spokesman for the related NEPTUN experiment. The UNK tunnel and our large underground cave are just about finished. The 60 m by 15 m SS-3 cave, which is about 50 m

underground, is shown in Fig. 8. Notice the cave's various extensions including the electronics room, the 55 m long NEPTUN-A cave, the long bypass tunnel, and the 9 m and 7 m diameter shafts to the surface. The beam enters from the right and passes through our polarized jet. The NEPTUN experiment consists of several different spectrometers, including: Solovianov's large forward spectrometer from IHEP-Protvino; Kazarinov's spectrometer from JINR-Dubna; and the polarimeter of Sarycheva from Moscow State University. Nikitin from Dubna also has an upstream spectrometer.

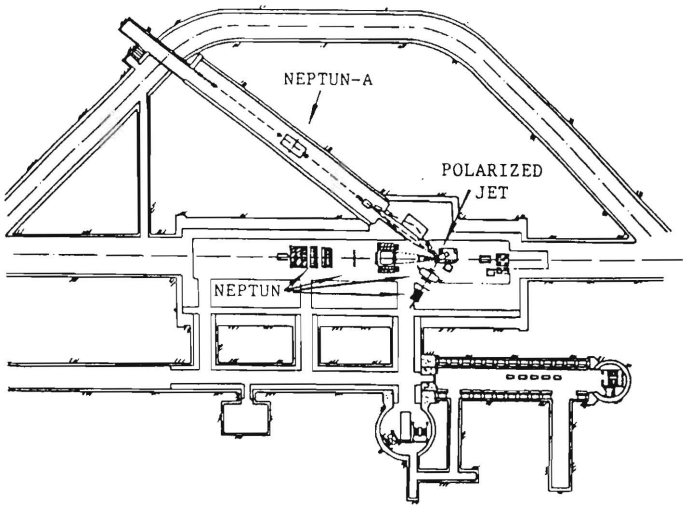

Fig. 8 SS-3 with NEPTUN-A and NEPTUN.

Our NEPTUN-A spectrometer will detect large-$P_\perp^2$ elastic p-p events by measuring the recoil proton's momentum with $\pm 0.1\%$ resolution. Michigan's largest contribution is the Ultra-cold Spin Polarized Atomic Hydrogen Gas Jet, which contains a 12 T solenoid magnet and a high power 0.35 K dilution refrigerator; this low temperature and high field produce a jet of spin polarized hydrogen atoms which will slowly cross the UNK beam. Our smaller Prototype Jet produces an intensity of 10^{16} s^{-1}. This Mark II Jet should have an intensity above 10^{17} s^{-1}; this will give a luminosity of 10^{32} cm^2s^{-1} with the planned UNK beam of 10^{19} s^{-1} protons passing through the Jet. We eventually hope to reach $L = 10^{33}$ cm^2s^{-1} which should allow precise measurements of A out to $P_\perp^2 = 8$ $(GeV/c)^2$ in p-p elastic scattering at 400 GeV. We plan to determine if the still unexplained spin effect persists at this energy.

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