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ACCELERATING POLARIZED PROTONS WITH SIBERIAN SNAKES

A. D. KRISCH
Randall Laboratory of Physics
University of Michigan
Ann Arbor, MI 48109-1120 U.S.A.

I will first briefly review the history of polarized proton beams and high energy proton spin experiments. Next I will discuss Siberian snakes and some possible high energy polarized proton beams at RHIC, HERA and Fermilab.

The first high energy polarized proton beam was accelerated at the ZGS in 1973. The ZGS polarized beam's design work started in 1969; for the first time one had to overcome depolarizing resonances. Fortunately, at the weak focusing ZGS, the resonances were not too strong and we did overcome them. [1] At that time, we did not yet know very much about polarized proton beams, but we were lucky.

The ZGS polarized proton beam operated from 1973 until 1979 and produced some exciting physics. Fig. 1 shows the p-p elastic cross-sections in different initial spin states plotted against $P_\perp^2$. [2] At small $P_\perp^2$ the spin-parallel and the spin-anti-parallel cross-sections are almost equal. But at large-$P_\perp^2$, where the protons' constituents directly interact, we found that the hard scattering component only occurs when the spins are parallel. When the spins are anti-parallel, the protons' constituents apparently pass through each other. This was a very surprising result in 1977; despite hundreds of theory papers, it still has not been adequately explained.

Bethe and Weisskopf then suggested that since, at 12 GeV, this spin effect was only large near 90°_{cm}, perhaps it was due to particle identity effects rather than large-$P_\perp^2$ hard scattering. To answer this question, we redid the experiment while holding fixed the center-of-mass scattering angle at exactly 90°_{cm} [3] and varying $P_\perp^2$ by varying the incident energy. We found that this large spin effect still occurred at the large-$P_\perp^2$ higher energy points, while from about 3 to 8 GeV/c, where $P_\perp^2$ was smaller, the spin asymmetry was small, although one was still at 90°_{cm}. I later made Fig. 2 [4] with some help from Prof. Haeberli, who is an expert on lower energy spin effects. This plot of the spin-spin asymmetry A_{nn} at 90°_{cm} shows dramatic structure below 2 GeV/c; then near 3 GeV/c the spin asymmetry drops to almost zero; perhaps this drop convinced many people that spin effects would disappear at high energy. But then A_{nn} rises dramatically near 8 GeV/c. This curve certainly did not confirm the belief that spin effects would disappear at high energy.

In the late 1970's some people were studying λ hyperons produced at Fermilab with both the beam and the target unpolarized. [5] By studying their decay distribution, they found that the λ's had a large polarization near $P_\perp = 1$ GeV/c. Moreover, the λs' polarization seems to be independent of energy. Fig. 3 shows, as dashed lines, the many small-error 400 GeV points from Fermilab; the 12 GeV KEK data and the 2000 GeV ISR data are also shown. These hyperon polarization data indicated that hadronic interactions have large spin effects that do not decrease with energy.

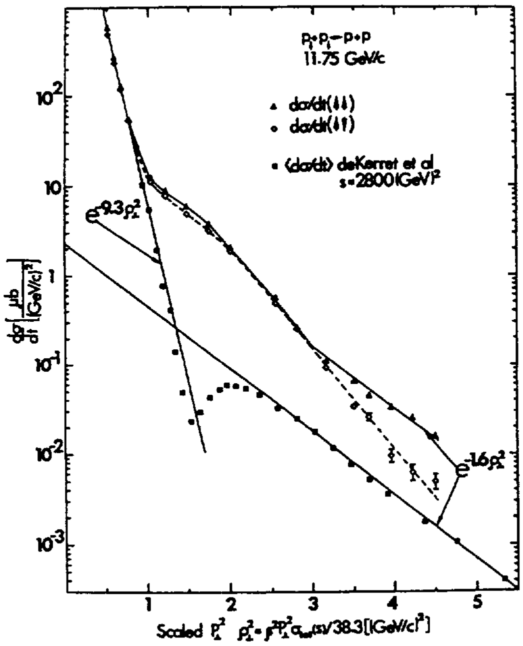

Fig. 1: Proton-proton elastic scattering cross-sections in parallel and anti-parallel initial spin states plotted against the scaled $P_\perp^2$ variable.[3]

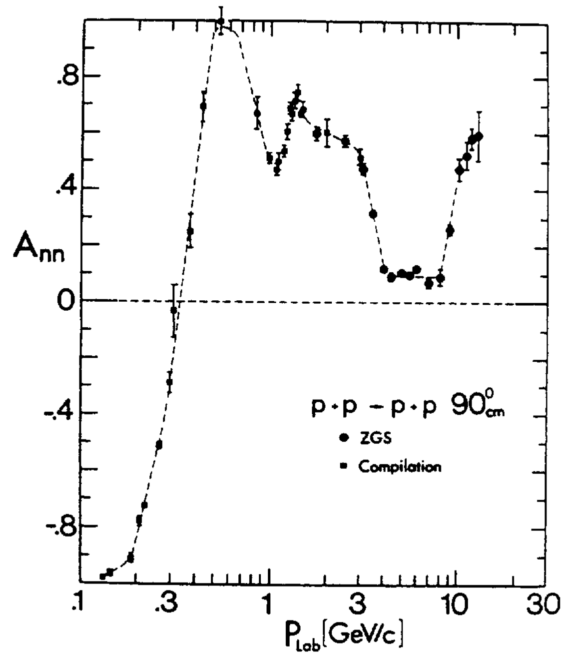

Fig. 2: Compilation of the proton-proton elastic spin-spin parameter at 90°_{cm}.[4]

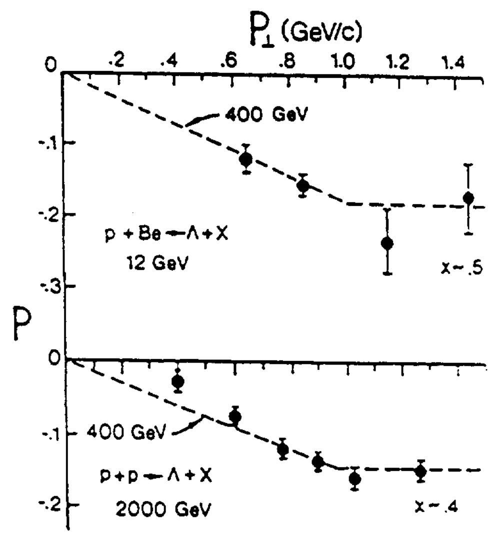

Fig. 3: Inclusive hyperon polarization data from Fermilab (400 GeV); KEK (12 GeV) and the CERN ISR (2000 GeV).[5]

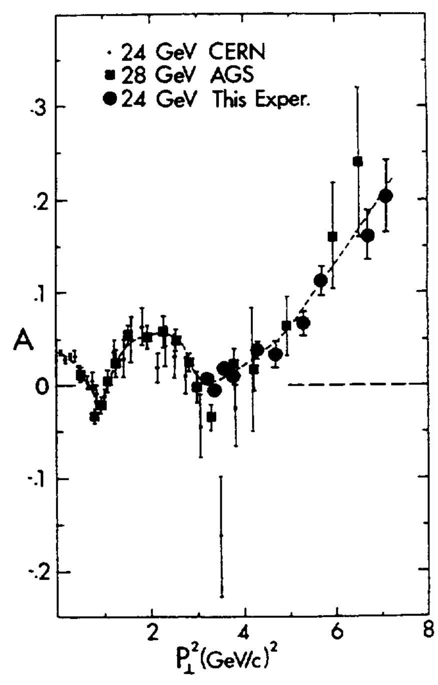

Fig. 4: The analyzing power A_n plotted against momentum transfer squared $P_\perp^2$ for proton-proton elastic scattering.[6]

Perturbative QCD predicted that spin effects should disappear at high energy and at large-$P_\perp^2$. Our 1985 to 1990 p-p elastic A_n Brookhaven AGS experiments at 24 and 28 GeV indicated that this prediction may not be true; the data are shown in Fig. 4. We first confirmed, with better precision, some CERN-Oxford small-$P_\perp^2$ data. We then built a much better polarized target, which allowed rather precise measurements at larger $P_\perp^2$. [6] The large-$P_\perp^2$ data clearly do not agree with the $A_n = 0$ prediction of perturbative QCD; apparently this is not a region of validity for PQCD.

A few years ago, Yokosawa's group at Fermilab, developed a 200 GeV polarized proton beam using this hyperon decay polarization. The intensity was too low for experiments at large-$P_\perp$; however, at moderate $P_\perp$ they did find a large A_n in inclusive $\pi^\pm$ production in 200 GeV p-p collisions. The asymmetries are large and are very different for π^+ and π^-, as shown in Fig. 5. [7]; this is more evidence that spin effects are large at high energy.

I will now turn to higher energy polarized proton beams. The Brookhaven AGS polarized beam design started at a 1977 workshop in Ann Arbor. [8] In 1984 the polarized beam started operating and some spin experiments started. Developing the AGS polarized beam was a difficult job, because the AGS is a strong focusing accelerator and its depolarizing resonances are quite strong. These depolarizing resonances occur when the spin precession frequency gets in phase with the frequency of passing through some horizontal magnetic fields. The proton's spin then has the same orientation each time it passes through these depolarizing fields; the resulting coherence can rapidly depolarize the proton beam.

Developing the AGS polarized beam cost about 10 Million 1980 Dollars and took about 5 years. To reach 22 GeV, we individually overcame 45 depolarizing resonances by tuning each to maximize the polarization; Fig. 6 is a typical tuning curve where we overcame the $G\gamma = 9$ imperfection resonance near 4 GeV. [9] Overcoming these 45 resonances required exclusive use of the AGS for 7 weeks; Dr. Samios, Brookhaven's Director, visited me about once a week in the AGS control room to politely remind me that these studies were costing \$1 Million a week. I am very pleased that we did accelerate the AGS polarized beam up to 22 GeV, but the 7 weeks of tune-up time cost about \$7 Million. Clearly this individual resonance correction technique was impractical for a much higher energy. The SSC would have had 36,000 depolarizing resonances; at the same tuning rate of one day per resonance, an SCC polarization tune-up would have required almost 100 years.

The electron people are much more fortunate. They do not have to overcome depolarizing resonances and do not have to build polarized sources. Around 1963 two bright Russian theorists, Sokolov and Ternov, [10] calculated that there should be some self-polarization; this occurs because the synchrotron radiation rates are slightly different when the spin is parallel or antiparallel to the ring magnets' field. At first, this was considered a clever theorical curiosity, but of little practical interest. However, this technique is now used at both the world's large electron rings, HERA and LEP. Moreover, the LEP depolarizing resonances allowed calibrating the intermediate Boson mass with the unusual precision of about 1 part in 10^4; without this self-polarization such precision would have been impossible. The late Sokolov and Ternov certainly deserve great credit for this clever idea.

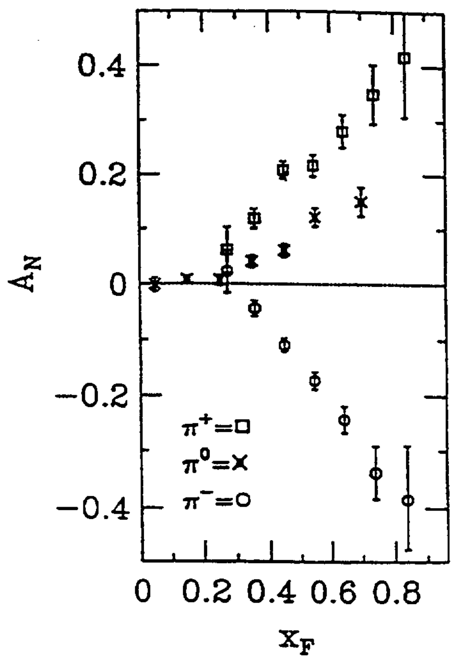

Fig. 5: Left-right asymmetry in inclusive pion production in 200 GeV p-p collisions at Fermilab.[7]

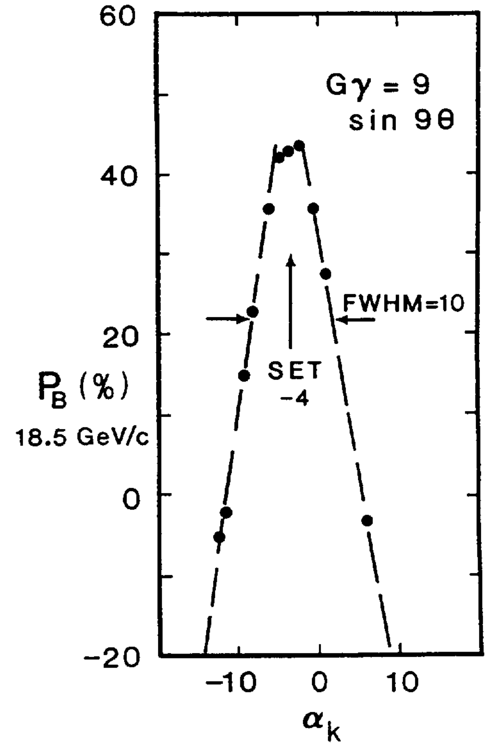

Fig. 6: Overcoming the $G\gamma = 9$ imperfection depolarizing resonance at the AGS.[9]

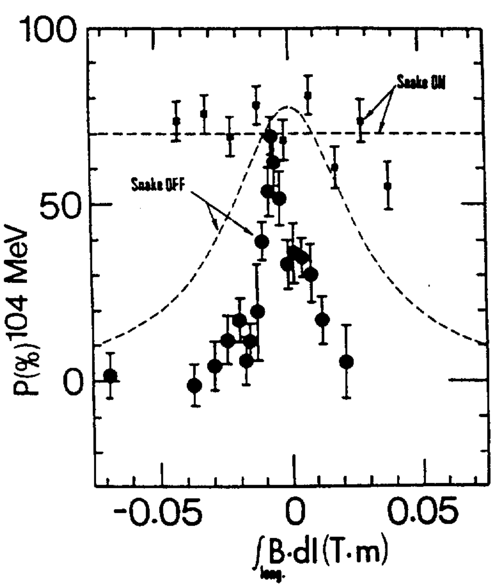

Fig. 7: Siberian snake overcoming the $G\gamma = 2$ imperfection depolarizing resonance at IUCF.[13]

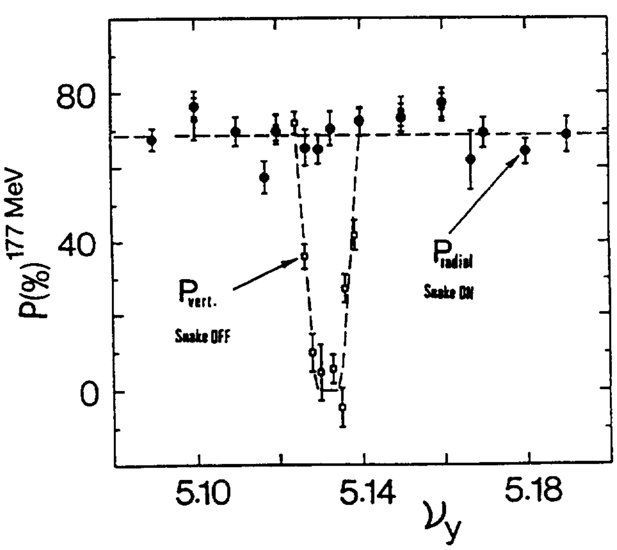

Fig. 8: Siberian snake overcoming the $G\gamma = 3 + v_y$ intrinsic depolarizing resonance at IUCF.[14]

Because of the proton's much smaller magnetic moment, one would need a 70 TeV proton accelerator before the Sokolov-Ternov self-polarization would become useful. Fortunately, around 1976, two other bright Russians, Derbenev and Kondratenko, [11] invented Siberian snakes. A snake rotates the spin direction by exactly 180° on each turn around a ring; this makes all the depolarizing fields cancel themselves. To understand snakes, let us assume that, before going around the ring, a proton starts with its spin vertically up at 0°. Then assume that all the depolarizing fields in one turn around the ring rotate the spin from 0° to 5°; after one turn, the snake rotates the spin by 180° to 185°. When the proton goes around the ring a second time, the same depolarizing fields now rotate its spin by 5° in the opposite directions from 185° back to 180°; finally the snake again rotates the spin by 180°, which returns it to 0°. The Siberian snake is a very clever idea; it makes the difficult-to-correct depolarizing fields cancel themselves.

At a 1985 workshop in Ann Arbor, [12] it became clear that accelerating polarized protons to very high energies would need Siberian snakes. Probably Ernest Courant already understood this during the 1977 Ann Arbor Workshop; I recall him trying to convince Owen Chamberlain and me that Siberian snakes were a great idea, but apparently with little success. In any case, in 1985 Courant finally convinced us, and off we went to try this idea at a new accelerator. The Indiana Cooler Ring was just coming on line; its energy was only about 500 MeV; however, it had 6-meter-long straight sections and we put a snake in one of them. The snake was a large superconducting solenoid of about 2 Tesla-meters, which was enough to rotate the spin by 180° up to a few hundred MeV.

Our first experiment with the Siberian snake is shown in Fig. 7. [13] We studied the $G\gamma = 2$ imperfection depolarizing resonance which always occurs near 108 MeV. With no snake, we got full polarization when we exactly corrected the field; however, any small imperfection field clearly killed the polarization. Fig. 7 looks quite similar to Fig. 6, where we individually corrected the $G\gamma = 9$ resonance at the AGS. On the other hand, with the Siberian snake turned-on, there was full polarization over the entire range. This result got a lot of attention. For some reason CNN decided that Siberian snakes were newsworthy; they broadcast a story about them five times. More importantly, a number of accelerators around the world are now using or designing Siberian snakes.

We did many other experiments. As shown in Fig. 8, we found that the Siberian snake could also overcome intrinsic depolarizing resonances. [14] We also studied: RF depolarizing resonances, which can calibrate the beam energy or flip the spin; synchrotron side band resonances; snake depolarizing resonances; partial Siberian snakes; and many other things unknown when the ZGS polarized proton beam was somehow accelerated in 1973.

After testing the Siberian snake idea, we formed the US-Russian-Japanese-Canadian SPIN Collaboration to try to get all the world's proton beams polarized. This Collaboration has had several permutations. It started in 1990 with the first SSC proposal EOI-001; this proposed to make 26 extra spaces in each SSC ring for the installation of Siberian snakes. [15] The SSC Management somewhat accepted the proposal; they actually changed the lattice to make 52 extra spaces of about 20 meters each for the later *possible* installation of Siberian snakes. But of course the SSC is now gone, so this is just history.

About then, in late 1990, John Peoples, Fermilab's Director, apparently became interested in accelerating polarized protons at Fermilab; during the next few years, Fermilab paid our SPIN Collaboration $366,000 for a 225-page Design Study Report. [16] We found that one could accelerate polarized protons with 6 Siberian snakes in the Tevatron, 2 snakes in the 120 GeV Main Injector, and some AGS-ZGS-type hardware in the 8 GeV Booster. This polarized beam project would cost about $20 Million including some accelerator modifications. We submitted the Report in July 1995; however, Fermilab's Management apparently soon decided that they did not then want to accelerate polarized protons.

In 1995, Bjorn Wiik, DESY's Director, was watching these studies because they involved testing a HERA dipole at DESY. When it was learned that Fermilab was apparently not planning to proceed, DESY commissioned our SPIN Collaboration to do a similar study for HERA and paid us 100,000 DM. In November 1996 we submitted the 92-page Design Study Report; [17] SPIN and DESY both got a good bargain because HERA is not very different from the Tevatron. We estimated that accelerating polarized protons in HERA would cost about 25 Million DM. The proposed HERA proton polarization hardware is shown in Fig. 9. Note that HERA's 820 GeV proton ring may be a bit more difficult to polarize than the Tevatron because it has 4-fold rather than 6-fold symmetry. For reasons which Courant and Derbenev understand, an odd number of pairs of snakes is best; thus, 6 snakes are much better than 4. The DESY Directors seem quite interested; however, because of recent financial problems, they can not even consider funding this project before 1999. Thus, they decided to provide our SPIN Collaboration with 200,000 DM for polarized beam R & D during 1997 and 1998.

I will end by discussing the RHIC polarized proton beam project that is now proceeding fairly quickly. The AGS now has a partial Siberian snake, which allowed them, during two runs in 1994, to successfully overcome [18] about 40 imperfection depolarizing resonances, without the earlier [9] painful correction studies; they are now working on the intrinsic depolarizing resonances. Brookhaven has decided to accelerate polarized protons at RHIC; the Japanese RIKEN contributed $20 Million to this project. The RHIC Siberian snakes, shown in Fig. 10, may be installed by 1999; [19] hopefully some RHIC polarized proton experiments could then start fairly soon. One should be able to make detailed studies of spin effects in p-p elastic scattering and in various inelastic channels. I certainly would like to see the data in Figs. 1, 2, 4 and 5 extended to higher $P_\perp^2$ and to higher energy; I think that this may be possible at RHIC.

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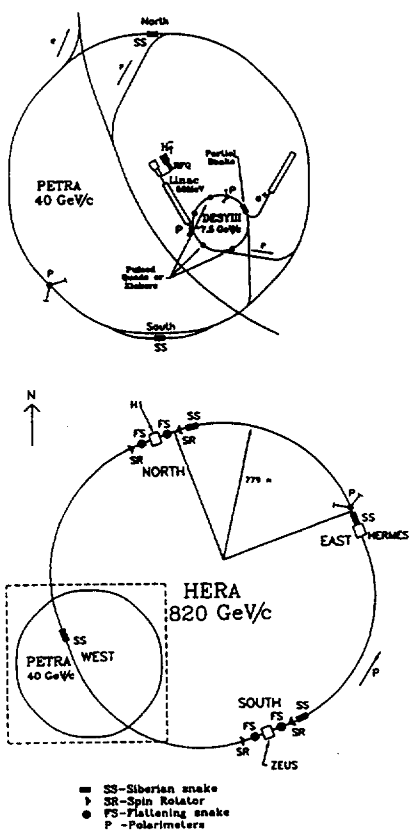

Fig. 9: The proposed 820 GeV HERA polarized proton beam at DESY.[17]

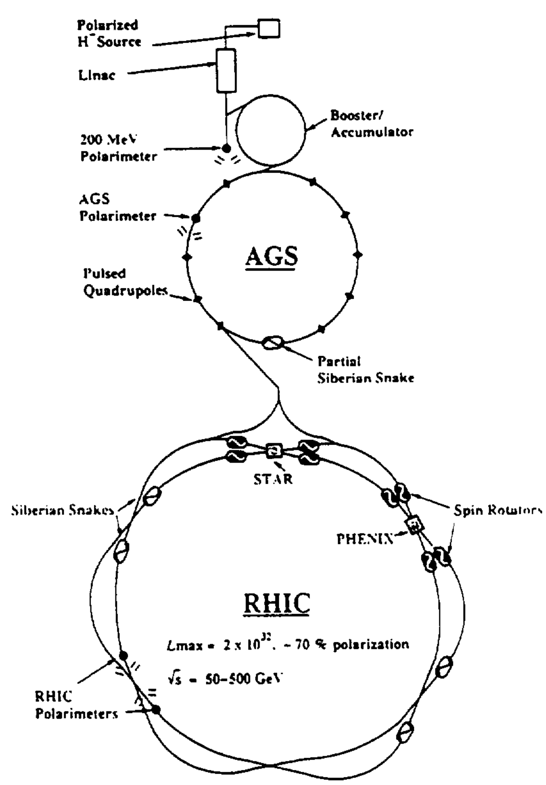

Fig. 10: Polarized Protons at RHIC.[19]