SSC Letter of Intent

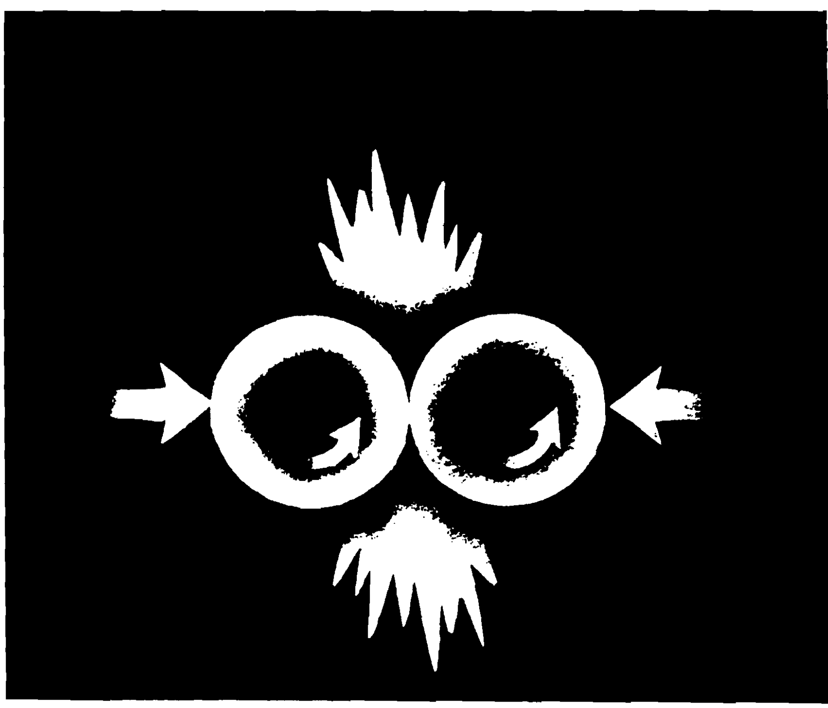
November 1990



# S P I N

## MICHIGAN INDIANA
## PROTVINO DUBNA MOSCOW
## KEK KYOTO





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## ABSTRACT


This is a Letter of Intent for a proposed SSC experiment **SPIN**, which would have two major goals:

1. Accelerate polarized protons to 2 TeV in preparation for later acceleration to 20 TeV.
2. Study spin effects in 2 TeV p-p elastic and inclusive collisions using a polarized gas jet internal target.


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## 1. PARTICIPANTS

The participants in SPIN would include **high energy**, **nuclear**, and **accelerator** physicists from the University of Michigan; Indiana University; IHEP, Protvino; JINR, Dubna; Moscow State University; KEK, Tsukuba; and Kyoto University. The current participants are 66 in total:


V. A. Anferov†, R. Baiod, J. A. Bywater, E. D. Courant, D. G. Crabb*, Ya. S. Derbenev‡, W. A. Kaufman, A. D. Krisch, A. M. T. Lin, T. W. O'Donnell, D. C. Peaslee, R. A. Phelps, R. S. Raymond, T. Roser, D. P. Stewart, J. A. Stewart, E. Tjukanov, B. S. Van Guilder, B. Vuaridel, V. K. Wong
THE UNIVERSITY OF MICHIGAN, ANN ARBOR, U.S.A.

J. M. Cameron, T. E. Ellison, D. L. Friesel, S. Y. Lee, M. G. Minty, T. Rinckel, M. A. Ross, P. Schwandt, F. Sperisen, E. J. Stephenson
INDIANA UNIVERSITY CYCLOTRON FACILITY, BLOOMINGTON, U.S.A.

Yu. M. Ado, V. A. Kachanov, V. Yu. Khodyrev, V. V. Mochalov, S. B. Nurushev, D. I. Patalakha, A. F. Prudkoglyad, V. V. Rykalin, V. P. Sakharov, V. L. Solovianov, A. G. Ufimtsev, M. N. Ukhanov, A. N. Vasiliev
INSTITUTE OF HIGH ENERGY PHYSICS, PROTVINO, U.S.S.R.

V. V. Fimushkin, M. V. Kulikov, V. G. Luppov, V. A. Nikitin, P. V. Nomokono, A. V. Pavlyuk, Yu. K. Pilipenko, V. B. Shutov, I. V. Zhibulin,
JOINT INSTITUTE FOR NUCLEAR RESEARCH, DUBNA, U.S.S.R.

A. I. Demianov, A. A. Ershov, A. M. Gribushin, N. A. Kruglov, A. S. Proskuryakov, A. I. Ostrovidov, L. I. Sarycheva, N. B. Sinejv, A. S. Yarov
MOSCOW STATE UNIVERSITY, MOSCOW, U.S.S.R.

N. Hiramatsu, Y. Mori, H. Sato, K. Yokoya
KEK, TSUKUBA, JAPAN

A. Masaike
KYOTO UNIVERSITY, KYOTO, JAPAN


The spokesperson for the SPIN Collaboration is:


A. D. Krisch
Randall Laboratory of Physics
The University of Michigan
Ann Arbor, Michigan 48109-1120 USA

Telephone: 313-936-1027
Telefax: 313-936-0794
Telex: 4320815 UofM UI
E-mail: KRISCH@UMIPHYS


† Permanent Address: Moscow State University

* Present Address: University of Virginia

‡ Permanent Address: Novosibirsk

## 2A. PHYSICS GOALS WITH 2 TEV POLARIZED PROTON BEAM

The primary 2 TeV physics goal of SPIN is to study two-spin and one-spin effects in proton-proton elastic scattering at large $P_\perp^2$. We would also study spin effects in inclusive p-p scattering. Our collaboration would first help to develop a 2 TeV spin-polarized proton beam using Siberian Snakes to overcome the many depolarizing resonances in the three SSC booster rings (See Appendix A and Section 3A). The 2 TeV polarized proton beam would then be scattered from a Polarized Proton Gas Jet used as an internal target. The elastic and inclusive events would be detected by a quadrupole-focusing high-luminosity spectrometer about 65 m long.

Both the Polarized Jet and the spectrometer would be quite similar to the devices now being constructed for our NEPTUN-A experiment; this fixed-target elastic and inclusive experiment is scheduled to run with an unpolarized beam at UNK starting in January 1993 at 400 GeV and then later at 3 TeV. It might also later run as a 400 GeV on 3 TeV collider experiment. The experience gained at UNK might be valuable to us at the SSC.

Much of SPIN is quite experienced with inclusive and elastic experiments. We made perhaps the world's first inclusive measurement in 1967 by studying $p + p \to x^\pm$ + anything at 12 GeV at the ZGS.[1] Our group then made the first inclusive measurements at the ISR in 1971[2] and confirmed Feynman-Yang scaling.

The spectrometer that we propose to use at the SSC would be quite similar in general concept to the 45 m long inclusive spectrometer used at the ISR[2] and the 55 m long elastic/inclusive spectrometer that will be used at UNK.[3]

There is also considerable experience with elastic scattering experiments at high $P_\perp^2$. We have carried out a number of p-p elastic scattering experiments[4,5] with unpolarized beams and targets. The break found in the unpolarized $90^\circ_{cm}$ p-p elastic experiment at the ZGS[5] in 1966 was perhaps the first experimental evidence for inner structure in the proton; the same $90^\circ_{cm}$ data were later used as the main experimental support for Brodsky's $s^{-n}$ scaling laws of QCD.

We are especially experienced in spin polarization experiments. Using the ZGS polarized proton beam, large and totally unexpected two-spin effects[6] were found in large-$P_\perp^2$ proton-proton elastic scattering. In the hard-scattering region near $P_\perp^2 = 5\ (\mathrm{GeV}/c)^2$, $d\sigma/dt(\uparrow\uparrow)$ was found to be four times larger than $d\sigma/dt(\uparrow\downarrow)$ as shown in Fig. 1. Concerns by Bethe and Weisskopf[6] about this being a $90^\circ_{cm}$ particle-identity effect rather than a large-$P_\perp^2$ hard-scattering phenomenon were directly answered by a fixed-angle experiment as shown in Fig. 2. The medium-$P_\perp^2$ points near $P_\perp^2 = 2.5\ (\mathrm{GeV}/c)^2$, where the spin effects are small, are just as much at $90^\circ_{cm}$ as the large-$P_\perp^2$ points near $P_\perp^2 = 5\ (\mathrm{GeV}/c)^2$ where the spin effects are large; thus it is clearly a hard-scattering phenomenon.

Other members of our collaboration have been active in polarization experiments at 70 GeV at Protvino, at 200 GeV at Fermilab, at 12 GeV at KEK, and at 10 GeV at Dubna. We also have a strong group of nuclear experts in spin experiments and accelerator physics.

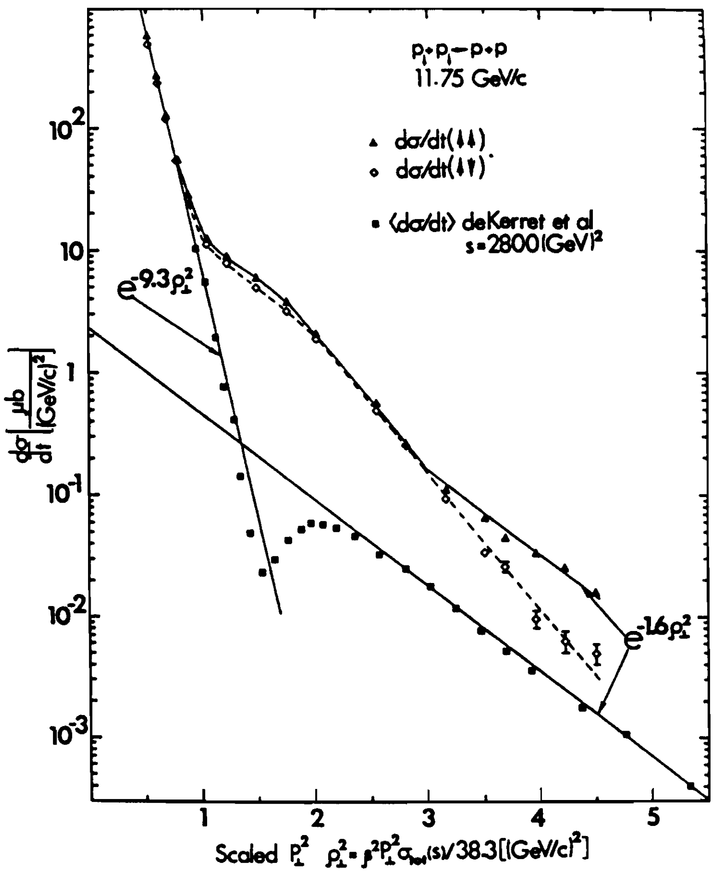


Figure 1. Spin-Polarized p-p elastic scattering cross-sections[6] plotted against the scaled $P_\perp^2$ variable.

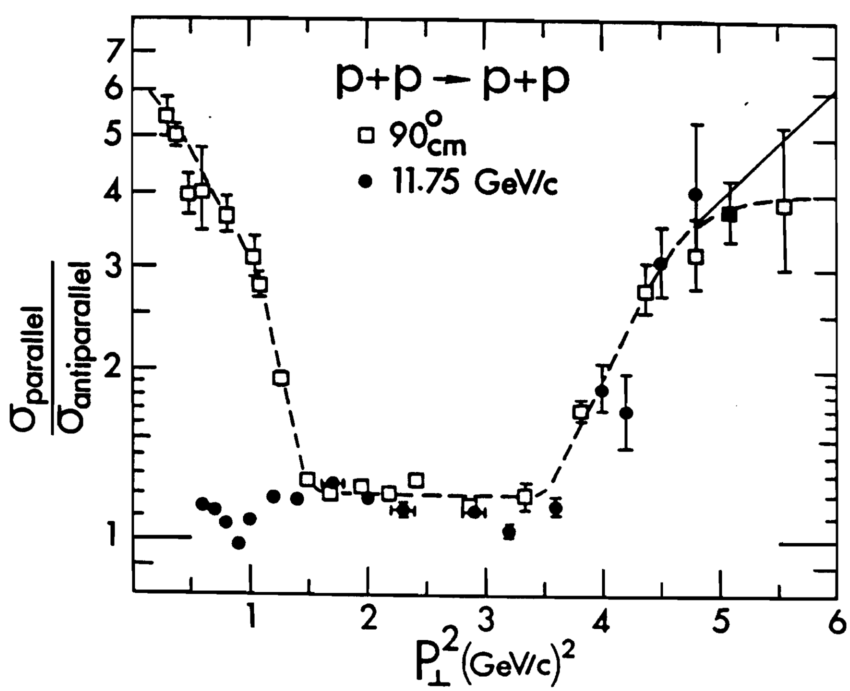


Figure 2. The ratio of the pure-spin p-p elastic cross-sections[6] plotted against $P_\perp^2$ for a fixed angle ($90^\circ_{cm}$) and a fixed energy (12 GeV).

More recently, large and again unexpected high-$P_\perp^2$ spin effects were found in measurements of the one-spin asymmetry, A, in p-p elastic scattering at the AGS[7]. It is quite clear that the once-accepted PQCD prediction, that A = 0 at high-$P_\perp^2$ and high energy, is not supported by the recent high precision data shown in Fig. 3. Because of the small cross-section, it seems unlikely that one can extend exclusive spin studies much beyond $P_\perp^2$ = 10 (GeV/c)$^2$; in fact the largest $P_\perp^2$ exclusive event ever observed[4] was at $P_\perp^2$ = 15 (GeV/c)$^2$.

The central physics goal of SPIN is to determine if the large spin-spin effects shown in Figs. 1 and 2 persist at 2 TeV. We would simultaneously, at no additional cost, study the TeV persistence of the one-spin A shown in Fig. 3; this study would extend and confirm the 1993-1995 NEPTUN-A experiment at UNK[3].

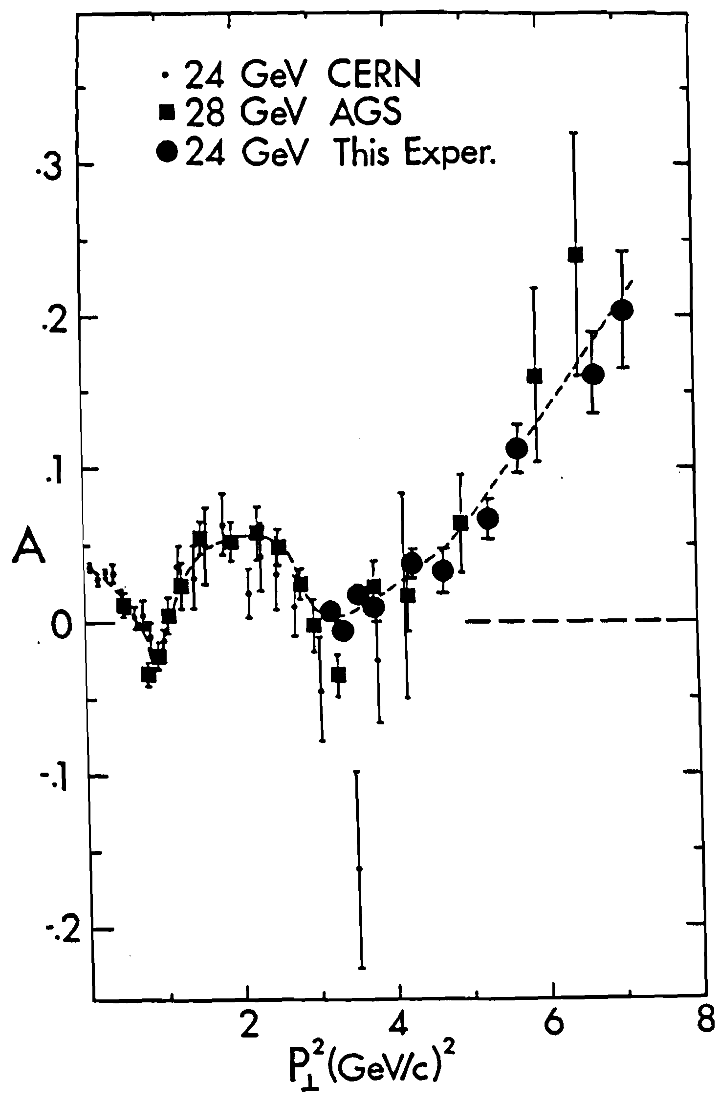


Figure 3. The analyzing power, A, is plotted against $P_\perp^2$, for spin-polarized proton-proton elastic scattering at 24 and 28 GeV/c[7].

## 2B. PHYSICS GOALS WITH POLARIZED BEAMS AT 20 TEV ON 20 TEV COLLIDER

The potential usefulness of polarization physics at SSC energies has been discussed by many people including: O. Chamberlain[8] in the Physics Working Group Summary at the Workshop on Polarized Beams at SSC, P. Taxil[9], M. B. Einhorn[10], E. Leader[11], M. Jacob et al.[12], J. Soffer[13], and most comprehensively, in the recent Review by C. Bourrely et al.[14]. The following brief summary, based on these reports, is provided for completeness.

Colliding beams of 20 TeV polarized protons at the SSC would give access to new observables which are not measurable with unpolarized beams. Spin experiments might reveal a definite signature for the underlying dynamics of parton and lepton interactions. Polarization experiments are an elegant technique for reducing the backgrounds and clarifying the signals for new physics. Spin studies have proved to be a powerful tool in the study of interactions at energies available today; one can expect a similar situation at SSC energies.

The polarization of each proton appears to be distributed among its constituent quarks and gluons. With polarized beams at the SSC the polarization distributions of the constituents in this new kinematic region could be measured by studying the direct production of $\gamma$, Z and $W^{\pm}$ with one or both of the proton beams polarized longitudinally. These processes should occur at high rates. The measurement of quark and gluon spin structure functions at low x is particularly interesting in light of the recent results from the EMC collaboration[15].

The 100% parity violating weak currents should cause a large longitudinal asymmetry in the production of Z, $W^{\pm}$ and $W^{+}W^{-}$ pairs. By studying these one-spin and two-spin helicity asymmetries ($A_L$ and $A_{LL}$) one can directly test the Standard Model of Electroweak Interactions with high precision at SSC energies.

Spin effects may give the most definitive signal for the production of new massive bosons (such as Higgs bosons) predicted by extensions of the Standard Model. A right-handed W boson, for example, could be identified by its longitudinal asymmetry $A_L$ whose sign would be opposite from that of the regular left-handed W boson. Such polarization experiments may also provide a unique technique for directly studying the nature of new Gauge bosons, right handed $W^{\pm}$ bosons, and other new physics such as an isoscalar Y boson, and an excited $W^*$ boson.

Spin measurements should also provide important tests of the Standard Model predictions for Strong Interactions. QCD calculations predict a positive value of the spin-spin asymmetry $A_{LL}$ for hadronic jet production. However, the jets produced by pairs of supersymmetric particles should have a negative $A_{LL}$; this could provide a unique signature for supersymmetric partners.

Polarized beams of protons might also be extracted at 200 GeV, at 2 TeV, and at 20 TeV and scattered from polarized or unpolarized fixed targets. Moreover, a polarized jet might be used as an internal target at 20 TeV. Adding polarized beam capability would allow a whole class of one-spin and two-spin elastic and inelastic proton-proton scattering experiments in both the fixed target and collider modes.

These are just a few examples of the importance of polarized beams at SSC energies. Detailed discussions of Spin Physics at SSC energies are given in the attached review by O. Chamberlain[8]

**(Appendix B)** and in the attached and much abridged comprehensive review by C. Bourrely, F. M. Renard, J. Soffer, and P. Taxil[14] **(Appendix C)**.

For some years many physicists believed that spin might become unimportant above a few GeV. The polarized beam and polarized target data shown in Figs. 1, 2, and 3 clearly demonstrate that spin dominates proton-proton elastic scattering at large-$P_\perp^2$ in the 10 to 30 GeV region. Fig. 4 shows that spin remains very important[16] in inclusive proton-proton scattering from 12 GeV at KEK, up to 400 GeV at Fermilab , and up to about 2 TeV equivalent at the ISR, the world's highest energy proton-proton collider. We see no evidence to indicate that spin will be any less important at TeV collider energies. We believe that precision measurements of spin observables may be necessary to understand the many new phenomena which we expect to be discovered at the SSC. **Spin-polarized beams will provide another important dimension to the SSC.**

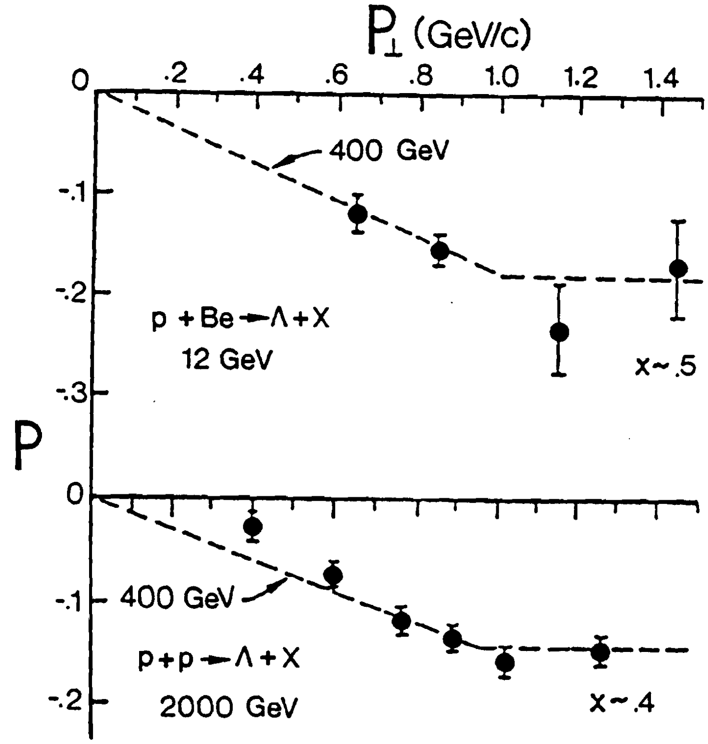


Figure 4. The polarization of lambdas produced by protons at 12 GeV and 2000 GeV plotted[16] against $P_\perp$. The line shows the polarization of 400 GeV lambdas.

## 3A. CONCEPTUAL DESIGN FOR POLARIZED BEAMS AT SSC USING SIBERIAN SNAKES

The plan for using Siberian Snakes to accelerate polarized protons to 2 TeV and then later to 20 TeV at the SSC is shown diagrammatically in Fig. 5 and described in detail in **Appendix A.** Our studies of Siberian Snakes at IUCF continue to produce promising results, some of which are shown in Figs. 6 and 7. We believe that many distinguished members of the world accelerator community would find the task of accelerating polarized protons at the SSC both challenging and intellectually exciting. If SSC responds positively to this Letter of Intent, our SPIN collaboration would probably be able to take an active role in helping to develop a polarized beam capability at SSC as was done at the ZGS[17], the AGS[18], and the IUCF Cooler Ring[19]. We believe that other experimental teams at the SSC might also benefit considerably from polarization capability.

Our SPIN collaboration is especially experienced in the acceleration and storage of polarized proton beams. Part of our collaboration played a leading role in the acceleration of polarized proton beams to 12 GeV at the Argonne ZGS[17] and to 22 GeV at the Brookhaven AGS[18]. Our collaboration contains most of the participants in the Siberian Snake tests at IUCF[19]. SPIN also contains many of the people responsible for polarized proton acceleration at the 12 GeV PS at KEK[20], for attaining 40% polarization of 29 GeV electrons at TRISTAN[21], and for attaining 10 GeV polarized deuteron acceleration at Dubna[22]. A number of experienced accelerator physicists from Protvino, Moscow, and Indiana further strengthens the group.

We have now exchanged a number of letters with the SSC Director about using Siberian Snakes in the SSC to accelerate polarized protons. We also studied the discussion of Polarized Beams at the SSC in the June 1990 Site-Specific Conceptual Design Report (pages 272–275). The July 31, 1990 letter from the SSC Director about our EOI-01 and the Summary of the PAC Snowmass Meeting appropriately concentrated on the acceleration of polarized beams at the SSC using Siberian Snakes. We are pleased that the PAC "held . . . that polarized beam capability for the SSC is of potential value".

We would like to address the Director's ". . understanding that the Siberian Snakes envisioned in [our] EOI could be installed in the SSC after it is built . ." and the PAC's statement that "polarized beam capability . . . could be added later". It is certainly possible to add Siberian Snakes to the 20 TeV Main Rings later **if** the appropriate spaces are kept empty in the ring lattices. We were pleased by Dr. Schwitter's direct answer to Dr. Diebold's question at the June 7, 1990 PAC Meeting: that appropriate spaces for Siberian Snakes would be left in the ring lattices, but that it was not yet decided if Snakes would be initially installed in these spaces. Much detailed work is needed before polarized protons can be injected into the 20 TeV Main Rings. We became more aware of this problem during our work of this past year. However, we do not believe that our SPIN collaboration or any other group is presently aware of all the potential difficulties in accelerating polarized beams to 20 TeV at the SSC. We are concerned that unless appropriate **early decisions** are made about the details of the various SSC rings, polarized beam capability may be **forever precluded** at the SSC.

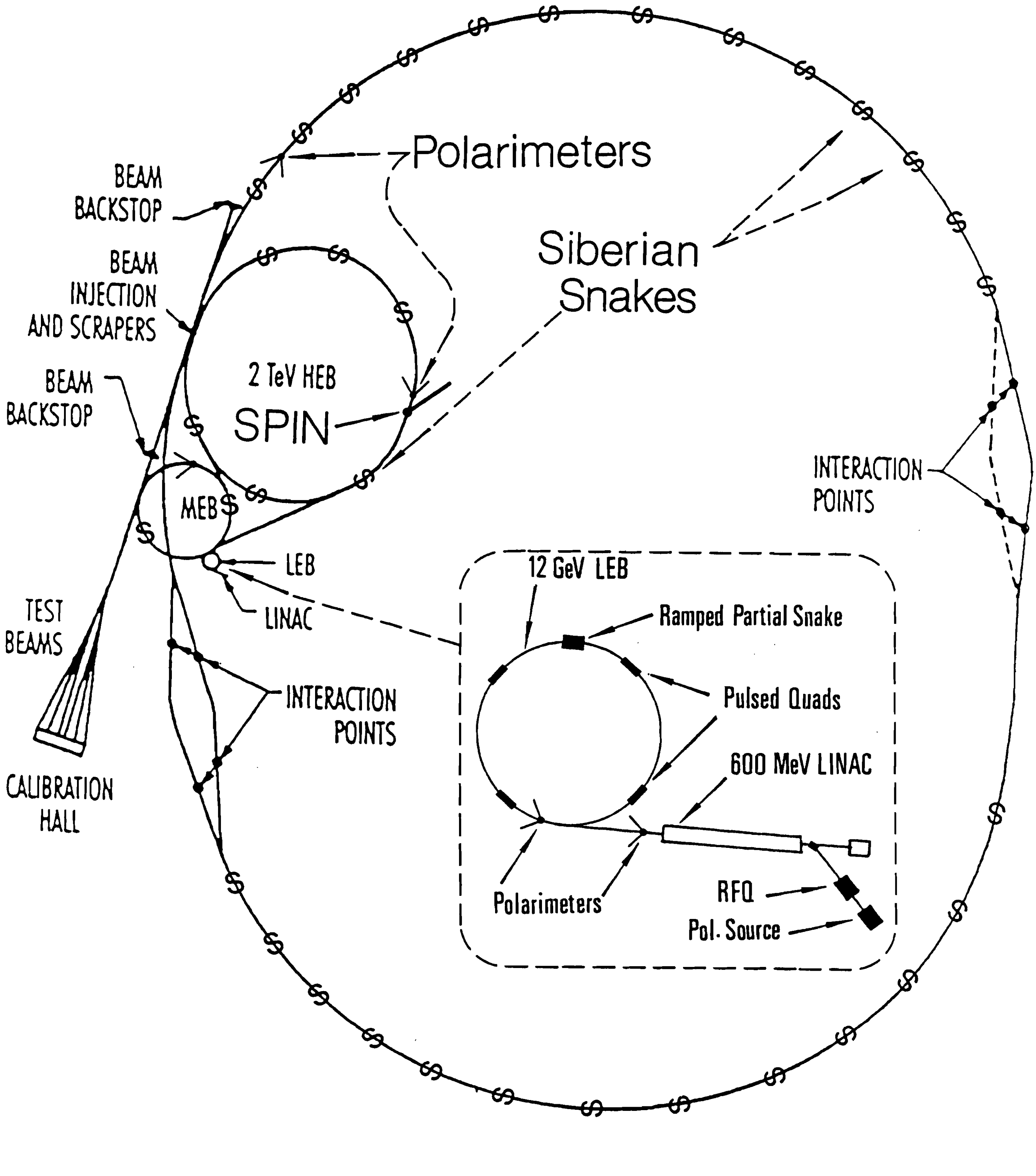


Figure 5. Proposed Polarized Proton Modifications at the SSC (not to scale).

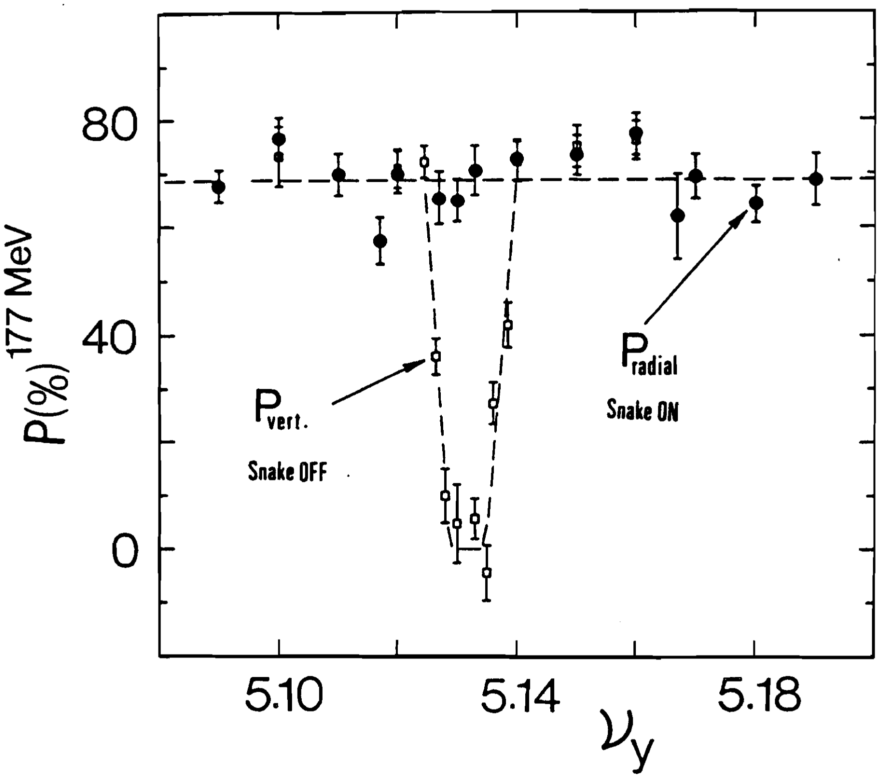


Figure 6. A Siberian Snake overcoming the $G\gamma = -3 + \nu_y$ depolarizing resonance at IUCF[19].

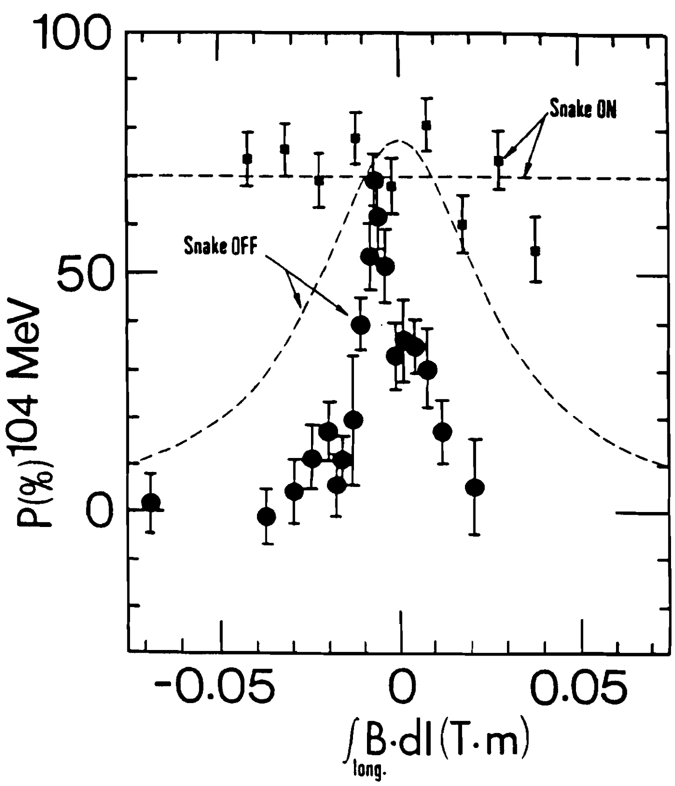


Figure 7. A Snake overcoming the $G\gamma = 2$ depolarizing resonance at IUCF[19].

We therefore propose the following plan:

1. Leave appropriate spaces in the SSC main rings for Snakes but **do not initially install Snakes in the 20 TeV Main Rings.**
2. Install, test, and commission all necessary low energy polarization hardware and then **accelerate polarized protons to 2 TeV prior to operation of the 20 TeV rings.**
3. Install a spectrometer, as in our EOI-01, and a polarized gas jet, as in NEPTUN-A at UNK, to study spin-spin effects in high-$P_{\perp}^2$ elastic and inclusive scattering at 2 TeV.
4. If this activity is successful, then one might allocate the additional funds necessary to install the 52 Snakes in the 20 TeV main rings.

The above plan of accelerating polarized protons to 2 TeV prior to the operation of the 20 TeV rings has five major advantages:

1. Some dedicated and knowledgeable accelerator physicists would work with your staff during SSC construction to ensure that polarized beam capability is **not accidently precluded.**
2. This plan gives a sizable reduction in the funds which must be committed in the near future; the estimated cost of a **2 TeV polarized beam is $18.3 M** (see Section 6).
3. It would be quite efficient to commission the polarized beam in the 12 GeV LEB, the 200 GeV MEB and the 2 TeV HEB during construction of the 20 TeV rings.
4. This plan would avoid the major **intangible cost** due to **SSC down-time** if the 2 TeV polarized beam hardware were installed after 20 TeV operation, when the SSC should be running as much as possible.
5. This 2 TeV plan might allow some interesting publications at the SSC in the mid-1990's in both Accelerator Physics and High Energy Physics.

Thus, we propose installing and using the 2 TeV polarized beam hardware during the early construction of the SSC. The numerous but simple 20 TeV Snakes could be installed in the late 1990's.

## 3B. CONCEPTUAL DESIGN FOR 2 TEV SPECTROMETER AND JET

### Polarized Gas Jet

We plan to build a Mark III ultra-cold spin polarized atomic hydrogen gas jet which will be an updated copy of the Mark II Jet that Michigan and MIT are building for NEPTUN-A. The Prototype Jet, shown in Fig. 8, is now delivering a flux of well above $10^{16}$ atoms per sec[23]. The Mark II Jet, shown in Fig. 9, is expected to give an intensity of about $10^{18}$ atoms per sec which would give an internal target thickness of about $10^{14}$ spin polarized protons per $cm^2$.

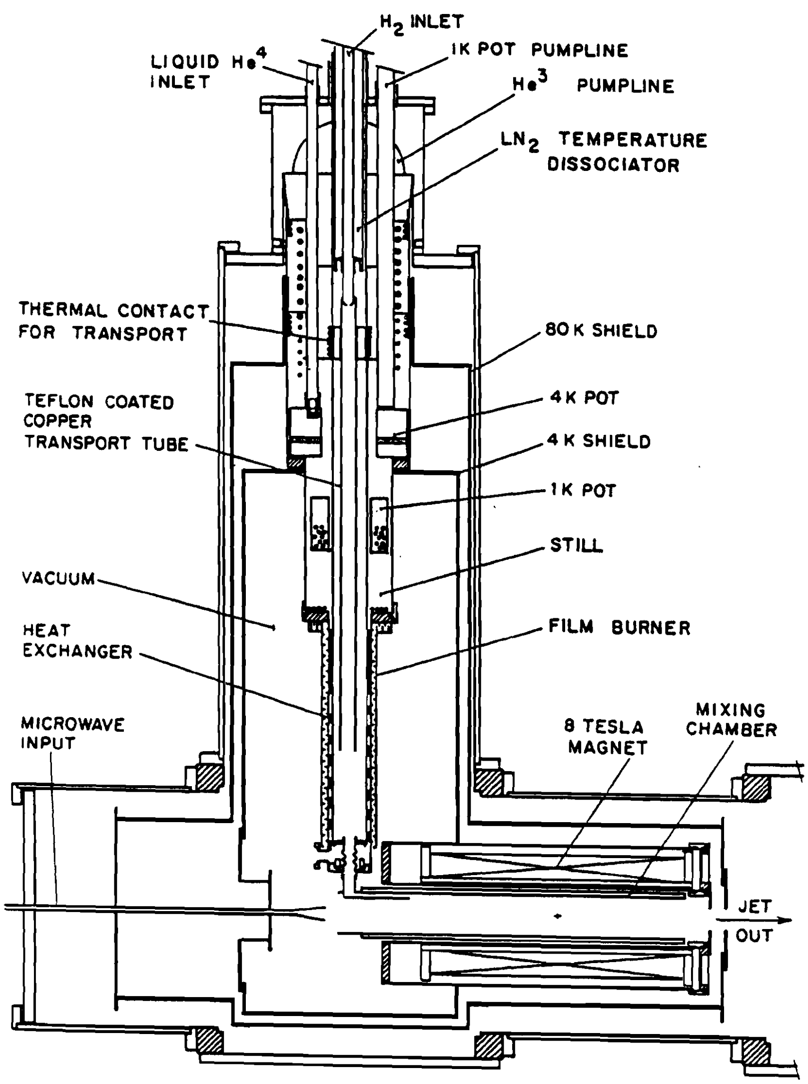


Figure 8. Prototype ultra-cold spin-polarized atomic hydrogen gas jet.

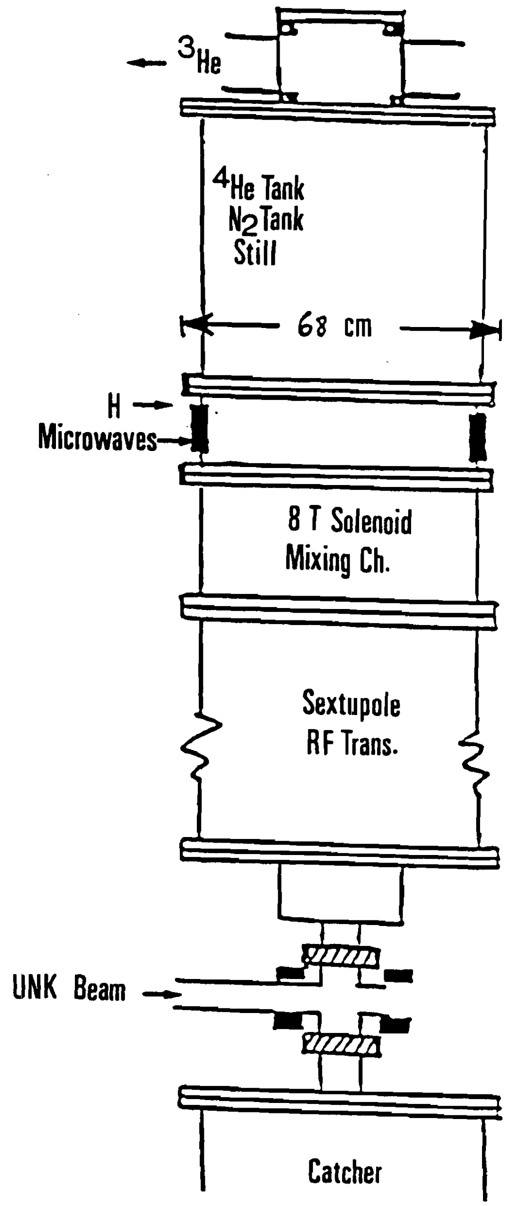


Figure 9. Mark II ultra-cold spin-polarized atomic hydrogen gas jet.

### Spectrometer

We plan to develop a spectrometer somewhat similar to our NEPTUN-A spectrometer, which should operate at 400 GeV and then 3 TeV at UNK. Our SPIN spectrometer at SSC would be about 65 m long with conventional 2 T steering magnets and with quadrupoles to focus a solid angle of about $\Delta\theta = 20$ mrad by $\Delta\phi' \equiv \Delta\phi \sin\theta = 200$ mrad into a size of about 25 cm x 50 cm at 65 m. This focusing and steering would allow small detectors and small aperture magnets and thus reduce the cost considerably. A drawing of the proposed SPIN spectrometer is shown in Fig. 10. Some more details of the spectrometer are discussed in Section 4B and in Section 6–Table 4. This spectrometer would allow us to detect p-p elastic events with good precision out to $P_\perp^2 = 8$ (GeV/c)$^2$ and inclusive events out to $P_\perp$ of about 20 GeV/c.

### Elastic Rates

The event rate is estimated for large-$P_\perp^2$ proton-proton elastic scattering at 2 TeV using a Mark III polarized gas jet and the proposed recoil spectrometer; this spectrometer has an acceptance of typically $\Delta t \sim 0.7$ (GeV/c)$^2$ and $\Delta\phi \sim 0.4$ rad. We assume that the Mark III jet target has a thickness of $10^{14}$ cm$^{-2}$ as at UNK. We also assume that the 2 TeV HEB ring has $10^{14}$ stored protons (5 $10^{10}$ per bunch in 2 TeV test beam mode), which implies that $3 \cdot 10^{18}$ protons per sec pass through the target. The resulting luminosity is then

$$L = 3 \cdot 10^{18} \cdot 10^{14} = 3 \cdot 10^{32}$$

Using the spectrometer acceptance of $\Delta t \cdot \Delta\phi/2\pi \sim 0.04$, and the measured $d\sigma/dt$, we then calculated the event rate using the equation:

$$\text{Events/hr} = L\, d\sigma/dt\, (\Delta t \cdot \Delta\phi/2\pi)\ 3600 \text{ sec/hr}$$

The errors in A and $A_{nn}$ are calculated assuming that the beam and target polarization are each 70%. With this luminosity our spectrometer should allow us to study spin effects in p-p elastic scattering out to $P_\perp^2$ of 8 (GeV/c)$^2$. The expected event rates for 2 TeV p-p elastic scattering with a polarized beam and a polarized target are given in Table 1 along with the errors in A and $A_{nn}$.

**TABLE 1 P-P ELASTIC EVENT RATES**

| $P_\perp^2$ [GeV/c]$^2$ | $d\sigma/dt$ nb/(GeV/c)$^2$ | $\frac{\text{Events}}{\text{hr}}$ | Hours | Events | $\Delta$ A $[.7\sqrt{\text{Events}}]^{-1}$ | $\Delta A_{nn}$ $[.49\sqrt{\text{Events}}]^{-1}$ |
|---|---|---|---|---|---|---|
| 2 | 37 | 1700 | 100 | 1.7 $10^5$ | 0.4% | 0.5% |
| 3 | 9.5 | 500 | 100 | 5 $10^4$ | 0.6% | 0.9% |
| 4 | 1.7 | 75 | 200 | 1.5 $10^4$ | 1.2% | 1.7% |
| 5 | 0.4 | 18 | 400 | 7 $10^3$ | 1.7% | 2.4% |
| 6 | 0.08 | 4 | 800 | 3 $10^3$ | 2.6% | 3.7% |
| 8 | 0.008 | 0.4 | 1200 | 400 | 7.1% | 10.2% |
| TOTAL | | | 2800 hrs | | | |

## Inclusives

For inclusive cross sections, this spectrometer would allow us to detect relatively slow secondary particles in the angular range of about 20 to 90° and in the momentum range of about 1 to 20 GeV/c. This range would allow us to use familiar and reliable detection techniques to study inclusive cross-sections.

With a 2 TeV fixed target the SPIN spectrometer would allow an inclusive range of $X_{\mathrm{Feynman}} = P_{\ell}/P_{\mathrm{cm}}$ of $\sim 0.0$ to $-1.0$, depending on the $P_{\perp}$ value. The maximum $P_{\perp}$ would be about 20 GeV/c. Since little is known about spin-spin effects in 2 TeV p-p inclusive cross-sections, it seems prudent to make the early exploratory inclusive measurements using an inexpensive and reliable technique. If exciting results are obtained, we might later propose to upgrade the spectrometer; or perhaps some other group might extend them using a larger detector in later 20 TeV on 20 TeV polarized running.

## Unpolarized Measurements

Notice that in addition to our proposed measurements of spin effects, this simple and inexpensive spectrometer would also allow us to measure unpolarized elastic and inclusive cross sections. It might be valuable to have such a simple and flexible spectrometer during the early operation of the SSC.

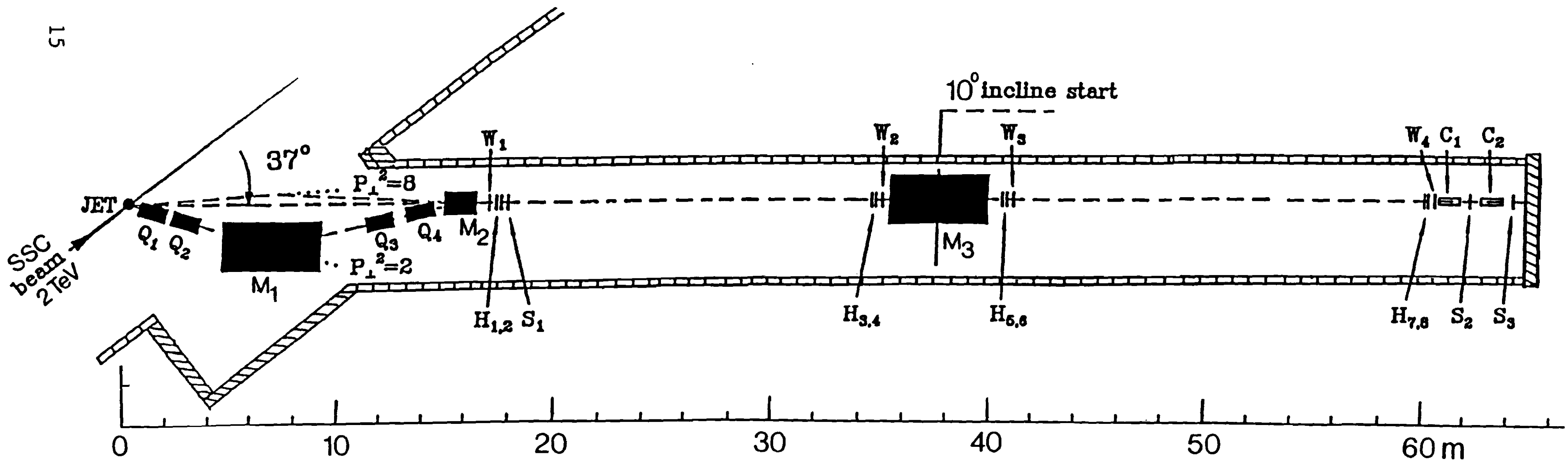


Figure 10. Spin Spectrometer.

## 4A. SCHEDULE AND MILESTONES: 2 TEV POLARIZED BEAM

| | |
|---|---|
| **Siberian Snake Studies at IUCF** | |
| Studies of Overlapping Depolarizing Resonances at IUCF | July 1991 |
| Preliminary Test of ramped Siberian Snake at IUCF | July 1992 |
| Final test of ramped Siberian Snake at IUCF | July 1993 |
| **SSC Polarized Beam Hardware** | |
| Preliminary design of Polarized Ion Source and RFQ | September 1991 |
| Preliminary design of MEB polarized hardware | September 1991 |
| Preliminary design of HEB polarized hardware | September 1991 |
| Preliminary design of Polarimeters | January 1992 |
| Preliminary design of LEB polarized hardware | January 1992 |
| Final design of Polarized Ion Source and RFQ | July 1992 |
| Final design of MEB polarized hardware | December 1992 |
| Final design of HEB polarized hardware | December 1992 |
| Final design of LEB polarized hardware | July 1993 |
| Final design of polarimeters | July 1993 |
| Final construction of polarimeters | July 1994 |
| Final construction of Polarized Ion Source and RFQ | July 1994 |
| Final construction of LEB polarized hardware | September 1994 |
| Final construction of MEB polarized hardware | September 1994 |
| Final construction of HEB polarized hardware | September 1994 |
| Test of polarimeters with unpolarized and polarized beams | September 1994–July 1995 |
| Installation of various polarimeters | December 1994–Sept. 1995 |
| Installation of Polarized Ion Source and RFQ | December 1994 |
| Installation of LEB polarized hardware | March 1995 |
| Installation of MEB polarized hardware | July 1995 |
| Installation of HEB polarized hardware | September 1995 |
| **SSC Polarized Beam Commissioning** | |
| Commissioning of Polarized Ion Source and RFQ | April 1995 |
| Commissioning of 600 MeV polarized beam | September 1995 |
| Commissioning of 12 GeV LEB polarized beam | January 1996 |
| Commissioning of 200 GeV MEB polarized beam | April 1996 |
| Commissioning of 2 TeV HEB polarized beam | September 1996 |

## 4B. SCHEDULE AND MILESTONES: 2 TEV SPECTROMETER AND POLARIZED GAS JET

### NEPTUN-A Spectrometer and Jet at UNK*

| | |
|---|---|
| Operation of Mark II Polarized Gas Jet in Ann Arbor | May 1992 |
| Operation of Mark II Jet in UNK beam | January 1993 |
| Final design of NEPTUN-A Spectrometer | June 1991 |
| Final construction of NEPTUN-A Spectrometer | September 1992 |
| Operation of NEPTUN-A Spectrometer in UNK beam | January 1993 |

### SPIN Spectrometer and Jet at SSC

| | |
|---|---|
| Preliminary design of SPIN Spectrometer | July 1991 |
| Preliminary design of Mark III Jet for SPIN | July 1992 |
| Final design of SPIN Spectrometer | July 1993 |
| Final design for 2 TeV underground and surface construction for SPIN | September 1992 |
| Final design of Mark III Jet for SPIN | July 1994 |
| Final construction of Mark III Jet for SPIN | September 1995 |
| Completion of 2 TeV underground and surface construction for SPIN | September 1995 |
| Final installation of SPIN Spectrometer and Mark III Jet | April 1996 |

### SPIN Running

| | |
|---|---|
| Commissioning of SPIN Spectrometer and Mark III Jet | September 1996 |
| Start of Physics | October 1996 |

* The inclusion of NEPTUN-A information is to reference the coordination and cross-fertilization between the two collaborations. All NEPTUN-A expenses will be provided by sources other than SSC.

## 5. DETECTOR PERFORMANCE SUMMARY

Since this SPIN Letter of Intent does not propose a large multi-purpose detector this section is not applicable.

We request being considered at this time to **avoid precluding** SSC polarized beams because of **accidental incompatibilities** in the design of the various rings.

We presently have no detailed plan for a detector to study 20 TeV on 20 TeV spin-polarized collisions. We might later consider collaborating with one of the large detector groups such as SDC, if they find this interesting; or we might consider moving the 2 TeV SPIN spectrometer to the 20 TeV rings with either minor or major modifications. Our present physics plans are sharply focussed on the proposed 2 TeV SPIN experiment in the mid 1990's.

## 6. BUDGET

For completeness we estimate the total cost of obtaining **20 TeV** polarization capability at the SSC, which would be about **$39.2 Million.** This estimate, which is given in Table 2, includes all Siberian Snakes, a polarized ion source, an RFQ, polarimeters, correction magnets and other associated hardware.

The budget for obtaining a **2 TeV polarized beam** is estimated to be **$18.3 Million** as shown in Table 3. This estimate also includes Siberian Snakes, a polarized ion source, an RFQ, polarimeters, correction magnets, and other associated hardware.

We estimate the budget for the **2 TeV SPIN spectrometer** and Polarized Gas **Jet**, including all associated construction and hardware to be **$27.0 Million.** This budget is described in some detail in Table 4.

Thus, the **total cost** of the now-proposed **2 TeV SPIN project** is:

| | |
|---|---|
| 2 TeV polarized proton beam capability at SSC | $18.3 Million |
| 2 TeV Spectrometer and Polarized Gas Jet | $27.0 Million |
| Total | **$45.3 Million** |

These estimates include 45% for contingency and inflation and are in FY 1991 Dollars. The estimates do not include the normal operating budgets for our various groups, which we expect would continue at about their present levels from U. S. DoE, U.S. NSF, U.S.S.R., and Japan.

The additional cost of accelerating polarized protons from **2 TeV to 20 TeV** is the difference between Tables 2 and 3 ($39.2 Million–$18.3 Million) = **$20.9 Million.** The total cost of our 2 TeV SPIN experiment plus 20 TeV polarized proton capability is **$66.2 Million.** Since polarized beams might be used by other experiments, it is not clear if the polarized beam cost should be fully assigned to our SPIN experiment.

## TABLE 2 20 TeV POLARIZED BEAM BUDGET ESTIMATE

Note that the cost is dominated by the 464 Siberian Snake dipoles for the 20 TeV Rings and the HEB. The cost of each 0.5 m long, 5 cm aperture, 2.7 T·m dipole was estimated by the SSC staff (R. Stefansky, G. Yost, R. Malner, and R. Steining) to be about \$22 K using the equation: **Cost = 1.3(\$12.5 K + length (meters) x \$8.5 K).**

| | |
|---|---|
| **1. Two 20 TeV rings:** | |
| 2 x 26 x 8 = 416 Siberian Snake Dipoles @ \$22 K | \$ 9.2 M |
| 2 Coulomb-Nuclear Interference Polarimeters | \$ 1.6 M |
| 2 "RF" Spin Flippers | \$ 0.6 M |
| 2 Symmetric Snake Spin Rotators | \$ 0.4 M |
| **2. HEB:** | |
| 6 x 8 = 48 Siberian Snake Dipoles @ \$22 K | \$ 1.1 M |
| 1 Coulomb-Nuclear Interference Polarimeter | \$ 0.8 M |
| 1 "RF" Spin Flipper | \$ 0.3 M |
| **3. MEB:** | |
| 2 x 8 = 16 Special Siberian Snake Dipoles @ \$50 K | \$ 0.8 M |
| 1 Coulomb-Nuclear Interference Polarimeter | \$ 0.8 M |
| 1 "RF" Spin Flipper | \$ 0.3 M |
| **4. LEB:** | |
| Rampable 4 T·m Solenoid | \$ 0.4 M |
| 4 Pulsed Quadrupoles with Power Supplies @ \$200 K | \$ 0.8 M |
| Internal Polarimeter | \$ 0.4 M |
| **5. LINAC:** | |
| 600 MeV Polarimeter | \$ 0.4 M |
| **6. RFQ:** | |
| RFQ | \$ 1.0 M |
| Switching Magnet, Beam Transport, and Vacuum | \$ 0.6 M |
| **7. Polarized Ion Source:** | |
| Conventional or Ultra-Cold | \$ 1.5 M |
| **8. Miscellaneous:** | |
| Computers, control modules, cables and interfaces | \$ 3.0 M |
| Helium connections and power supplies for 60 Snakes at \$50 K each | \$ 3.0 M |
| Subtotal | **\$27.0 M** |
| Inflation & Contingency 45% | \$12.2 M |
| **Total (in FY 1991 Dollars)** | **\$39.2 M** |

## TABLE 3 2 TeV POLARIZED BEAM BUDGET ESTIMATE*

This estimate is similar to the 20 TeV estimate, but with the main ring Snakes and their He connections and power supplies eliminated. The full computer and control system is included.

| | |
|---|---|
| **1. HEB:** | |
| 6 x 8 = 48 Siberian Snake Dipoles @ $22 K | $ 1.1 M |
| 1 Coulomb-Nuclear Interference Polarimeter | $ 0.8 M |
| 1 "RF" Spin Flipper | $ 0.3 M |
| **2. MEB:** | |
| 2 x 8 = 16 Special Siberian Snake Dipoles @ $50 K | $ 0.8 M |
| 1 Coulomb-Nuclear Interference Polarimeter | $ 0.8 M |
| 1 "RF" Spin Flipper | $ 0.3 M |
| **3. LEB:** | |
| Rampable 4 T·m Solenoid | $ 0.4 M |
| 4 Pulsed Quadrupoles with Power Supplies @ $200 K | $ 0.8 M |
| Internal Polarimeter | $ 0.4 M |
| **4. LINAC:** | |
| 600 MeV Polarimeter | $ 0.4 M |
| **5. RFQ:** | |
| RFQ | $ 1.0 M |
| Switching Magnet, Beam Transport, and Vacuum | $ 0.6 M |
| **6. Polarized Ion Source:** | |
| Conventional or Ultra-Cold | $ 1.5 M |
| **7. Miscellaneous:** | |
| Computers, control modules, cables and interfaces | $ 3.0 M |
| Helium connections and power supplies for 8 Snakes at $50 K each | $ 0.4 M |
| Subtotal | **$12.6 M** |
| Inflation & Contingency 45% | $ 5.7 M |
| **Total (in FY 1991 Dollars)** | **$18.3 M** |

* Note that some of the cost in the lower energy stages might be saved by transferring some appropriate equipment from other labs. In 1980 about $3 M was saved by transferring magnets, ferrite, and polarized sources from the ZGS to the AGS.

## TABLE 4 SPECTROMETER AND JET BUDGET

| | | | |
|---|---|---|---|
| 1. | Polarized Gas Jet, Mark III | | \$ 1.5 M |
| 2. | Spectrometer, Magnets, Power Supplies, and Stands | | \$ 2.5 M |
| 3. | Detectors | | \$ 1.5 M |
| 4. | Computers | | \$ 0.3 M |
| 5. | EDIA (Detector & Computer) x 20% | | \$ 0.4 M |
| 6. | Underground Facilities | | \$ 4.6 M |
| | a. Rear Spectrometer Hall (65 m) | \$3.5 M | |
| | b. Jet Hall | \$0.5 M | |
| | c. AE/CM @ 14% | \$0.6 M | |
| 7. | Hall Infrastructure (Underground facilities) x 10% | | \$ 0.5 M |
| 8. | Surface Facilities | | \$ 3.4 M |
| | a. Headhouse | \$0.75 M | |
| | b. Construction Shaft | \$0.25 M | |
| | c. Assembly Building | \$0.32 M | |
| | d. Machine Shops | \$0.16 M | |
| | e. 1/5 Admin./Lab Building | \$1.00 M | |
| | f. 1/2 Utilities Building | \$0.50 M | |
| | g. AE/CM @ 14% | \$0.42 M | |
| 9. | Site and Infrastructure (15% of SF) | | \$ 0.5 M |
| 10. | R & D | | \$ 1.0 M |
| 11. | Cryogenics (for Jet) | | \$ 0.5 M |
| 12. | Special Utilities | | \$ 0.6 M |
| 13. | Gas | | 0 |
| 14. | Detector related structures | | \$ 0.5 M |
| 15. | Safety Interlocks | | \$ 0.8 M |
| | | **Raw Subtotal** | **\$18.6 M** |
| | | Contingency & Inflation @ 45% | \$ 9.4 M |
| | | **Total** | **\$27.0 M** |

## 7. MANAGEMENT PRIOR TO SUBMISSION OF FORMAL PROPOSAL

To date the management of SPIN has been somewhat informal. The spokesperson has had periodic interactions with the various members of the collaboration through visits, telephone, fax, E-mail, and telex. For the moment this somewhat informal management style seems to be working effectively; this is partly because most members of SPIN have collaborated in the past. Nevertheless, we see the clear need for changes in the future as the activity grows.

## 8. MANAGEMENT AFTER APPROVAL

Our present plan would be to use a management style combining elements of the management techniques used in the AGS polarized beam project and the NEPTUN-A experiment at UNK.

This would include typically biweekly meetings on specific topics attended by the local and visiting experts on each topic. Reports of the meetings would then be distributed to each institution by E-mail or fax normally after minor editing by the spokesperson.

Twice each year a formal collaboration meeting would be held where all participants would be invited. (For NEPTUN-A the September Meeting is in the USSR and the April Meeting is in the USA.) Copies of all transparencies would be distributed to all institutions in the SPIN collaboration and the Highlights of the Meeting would be distributed to all members of the collaboration plus other interested persons.

The Highlights would be written by the spokesperson in close collaboration with senior physicists from each institution. The Highlights would define the progress and future direction of the SPIN program. Issues on which a clear consensus is not easily reached would normally be settled in smaller meetings with senior people from each involved institution. This works smoothly at NEPTUN-A and worked quite well with the AGS polarized beam project.

The transparencies and Highlights would form a permanent and dated record of the progress and problems of the SPIN project.

While no past experience can exactly match an SSC project, NEPTUN-A and the AGS polarized beam project have some similarities. NEPTUN-A involves 38 US and USSR physicists working on the first experiment at the 21 km circumference UNK. The AGS polarized beam project had a budget of about $10 M and a staff of about 80 scientists, engineers, technicians, and students from Argonne, Brookhaven, Michigan, Rice, and Yale. The successful Siberian Snake Collaboration at IUCF provides further experience in polarized beam project management, although the scale is somewhat smaller.

Our preliminary plan would be to designate for each major part of the SPIN project several contributing institutions and possibly a lead institution. A possible list might be:

| | |
|---|---|
| 1. Polarized Beam Theory | Michigan-Moscow-KEK-Protvino-IUCF |
| 2. Polarized Ion Source | Michigan-Dubna-IUCF-KEK |
| 3. RFQ | Protvino-Michigan |
| 4. Beam transport to LINAC | IUCF-Michigan |
| 5. LEB Polarization Hardware | IUCF-Michigan |
| 6. MEB Snakes | Michigan-Protvino |
| 7. HEB Snakes | Michigan-Protvino |
| 8. Polarimeters (Low Energy) | KEK-IUCF |
| 9. Polarimeters (High Energy) | Protvino-Kyoto-Michigan |
| 10. Computers and Control | Michigan-KEK-Protvino |
| 11. Polarized Gas Jet | Michigan-Dubna |
| 12. Spectrometer | Protvino-Moscow-Michigan-Kyoto |
| 13. Detectors and Computers | Michigan-Kyoto-Dubna-Moscow |

## 9. ADDING ADDITIONAL MEMBERS TO SPIN

Any physicist with a serious interest and experience in large-$P_\perp^2$ spin experiments or in the acceleration of polarized beams may apply to join the SPIN collaboration by contacting the spokesperson by mail, telephone, telex, E-mail, or fax using the information given in Section 1.

The SPIN collaboration has grown rapidly this year:

| | | | |
|---|---|---|---|
| 4 May 1990 | EOI | 17 people | Michigan |
| 7 June 1990 | PAC presentation | 38 people | Michigan, Protvino, Dubna |
| November 1990 | LOI | 66 people | Michigan, Indiana, Protvino, Dubna, Moscow, KEK, Kyoto |

We do not expect this rapid growth to continue, but a small number of qualified people would be welcome. Because of the magnitude of the task of accelerating polarized protons to 2 TeV and then possibly to 20 TeV, there is a special interest in adding appropriate accelerator physicists. A small number of accelerator experts from SSC would be especially valuable.

## 10. REQUEST FOR FY 1991 FUNDS*†

A principal activity during 1991 would be to produce more detailed designs for the polarization hardware and accelerator procedures in HEB, MEB, LEB, and the RFQ and Polarized Ion source. Another main activity would be the design, construction, and commissioning of a rampable superconducting solenoid for partial Siberian Snake studies at the IUCF Cooler Ring (see Section 4A). We also plan to study overlapping depolarizing resonances using the 10 kW RF Solenoid that we are now constructing. These two studies would be directly applicable to the acceleration of polarized protons at respectively the LEB and HEB of SSC. We would also begin detailed studies of the SPIN spectrometer and polarized gas jet (see Section 4B).

Our request for funds for FY 1991 for the SPIN collaboration is:

| | |
|---|---|
| 1. 3 FTE Accelerator Physicists at Michigan | \$150,000 |
| 2. Computing, running, and travel expenses | \$ 40,000 |
| 3. 50% of rampable Superconducting Solenoid for Siberian Snake studies at IUCF | \$125,000 |
| 4. Local travel and per diem expenses for 3 FTE Soviet and/or Japanese Accelerator Physicists | \$ 45,000 |
| 5. 1 FTE Experimental Physicist at Michigan | \$ 50,000 |
| 6. Travel and per diem expenses for Soviet and/or Japanese Experimental Physicists | \$ 15,000 |
| 7. 2 FTE Accelerator Physicists at Indiana | \$100,000 |
| Total | \$525,000 |

We request that \$425,000 of the funding go to Michigan and that \$100,000 go to Indiana. The contact person at Indiana would be J. M. Cameron, Director of IUCF. Michigan would then cover the local expenses of the Soviet and Japanese accelerator physicists and/or experimentalists while in the U.S.A.

Because of the relatively small size of the request it will not be prioritized in great detail. However, the accelerator work (Items 1, 2, 3, 4 and 7) should have higher priority than the experimental work (Items 5 and 6).

* includes benefits and overhead

† assumes that all groups will continue to receive their normal operating budgets from U.S. DoE, U.S. NSF, U.S.S.R., and Japan.

# APPENDIX A ACCELERATION OF POLARIZED PROTONS AT THE SSC USING SIBERIAN SNAKES

## SIBERIAN SNAKES

We will first describe a Siberian Snake[24,25]. It is typically a string of 8 short dipole magnets; its purpose is to maintain the spin-polarization by rotating the protons' spins by 180° while remaining "optically transparent". Optical transparency means that there is **no effect** on the beam orbit except within the Snake. Thus ideally there should be no effect on the beam dynamics and emittances outside of the Snake. We estimate that the Snake magnets' edge fields may shift the betatron tune by 0.0015 at injection into the 20 TeV rings. This should have a negligible effect on beam emittance and should require no correction.

There are two types of Siberian Snakes: Type 1 Snakes rotate the spin about a longitudinal axis, while Type 2 Snakes rotate the spin about a radial axis. Each of the 8 magnets in a Snake must rotate the spin by 90° about either a radial or vertical direction. The order of these rotations[26,27] determines whether it is a Type 1 or Type 2 Snake. To maintain vertical polarization one must use matched pairs of Type 1 and Type 2 Snakes or properly matched pairs of hybrid Snakes. Thus, there should always be an even number of Snakes in any ring with strong depolarizing resonances.

The great power of the Snake concept is that the same $\int B \cdot d\ell = 2.74\ T \cdot m$, which rotates the spin by 90° at 2 TeV injection, will also rotate the spin by 90° at 20 TeV. [Note that the exact formula is $\int B \cdot d\ell = \beta \cdot 2.74\ \mathrm{T \cdot m}$] Thus once a Snake is properly tuned for the first resonance it is properly tuned for all resonances. The number of Snakes needed in each stage of the SSC depends on the strength of its depolarizing resonances which grows[28] as $\sqrt{\mathrm{E}}$. If there were only one Snake in each 20 TeV ring, then the many betatron oscillations in a single turn would result in significant depolarization before the proton reached the Snake. Thus there must be a Snake every few kilometers. Optimized distributions of Siberian Snakes have been proposed by Steffen[26,27], Lee and Courant[28], and Yokoya et al[24].

Accelerator experts believe[24–28,30–35] that Siberian Snakes are capable of overcoming all depolarizing effects provided that the maximum strength of the depolarizing resonances ($\epsilon$) divided by the number of Snake pairs (N) is considerably less than the strength of a Snake pair, which is 1. The Snakes then dominate and control the spin motion. Since $\epsilon$ should reach about 5 at the SSC, we propose using 13 Snake pairs[28]; this would make $\epsilon/\mathrm{N} \sim 0.4$ which is adequately below 1. It is best if N is an odd number.

One example of a higher order effect could be overlapping depolarizing resonances. These have never been observed at GeV energies, but could exist at the SSC because the large $\epsilon$ could make the resonances wider than their separation which is always 530 MeV for imperfection resonances. Calculations indicate[28] that 26 snakes should be adequate to preserve 20 TeV polarization in the presence of overlapping resonances. We are approved at Indiana with high priority to study overlapping depolarizing resonances by using a new RF solenoid to induce a depolarizing resonance which can be made to overlap with the $G\gamma = 2$ imperfection resonance or the $G\gamma = \nu_y - 3$ intrinsic resonance. We have now induced an RF depolarizing resonance[36]. We expect to begin taking data on overlapping resonances during Spring 1991.

Another such effect is the possible existence of "Snake Resonances" which are a type of depolarizing resonance enhanced by the Snakes themselves. These have been studied extensively in theoretical papers[24–28,30–35]. After some effort, we now have seen the first evidence for a Snake resonance at Indiana[36]. We plan to study it in more detail next year.

Properly distributing the Snakes in each SSC lattice should make the accelerator much less sensitive to depolarizing effects. One interesting distribution process was named "Strong Spin Matching" by K. Steffen[26,27]; this technique was included in the distributions discussed earlier[24,26,28].

## DETAILED SSC MODIFICATIONS

### 20 TeV Rings:

About 26 Snakes (13 pairs) should be placed in each ring for a total of 52 Snakes. Each Snake, containing eight 0.5 m long dipole magnets with 5 cm gaps, might be placed in a 7 to 10 m long space in an appropriate[24,26,28] lattice cell.

### 2 TeV High Energy Booster (HEB):

About 6 Snakes (3 pairs) of 5 cm gap dipoles might each be placed in an appropriate[32] 7 to 10 m long space. The Snakes would shift the tune in the HEB by about 0.03 at 200 GeV injection; one should probably compensate this shift by properly ramping the ring quadrupoles. There should again be a negligible effect on emittance.

### 200 GeV/c Medium Energy Booster (MEB):

The 2 Snakes (1 pair) might be placed on opposite sides of the ring. The 16 Snake magnets, each about 0.5 m long with $\int B \cdot d\ell = 2.74$ T · m, should probably be about 8 cm wide to deal with the approximately 25 mm orbit excursions inside the Snake at the 12 GeV injection energy. The Snakes would shift the tune by about 0.15 at injection; by properly ramping the ring quadrupoles one could compensate this shift and avoid emittance growth which might be a factor of two without compensation.

### 12 GeV/c Low Energy Booster (LEB):

It would probably be easiest to use a single weak Partial Snake of about 10% (18° rotation) to overcome the fairly weak imperfection resonances; this would eliminate the large orbit excursions inside a normal Snake near injection at 1.2 GeV/c. Four modest pulsed quadrupoles with a few microsecond risetime should easily overcome the fairly weak intrinsic resonances. The easiest Partial Snake would probably be a ramped superconducting solenoid with a maximum $\int B \cdot d\ell \sim 4$ T · m at 12 GeV/c. Indiana and Michigan could provide both this Partial Snake and the pulsed quadrupoles.

### 1.2 GeV/c (600 MeV) LINAC:

There is no depolarization in the LINAC; thus no changes are required.

**RFQ:**

We would suggest a separate RFQ for the polarized proton source. As at the AGS, this would allow testing and maintenance of the polarized source during operation of the unpolarized source. There is no depolarization in an RFQ. Protvino might provide the RFQ.

**Polarized Ion Source:**

A conventional atomic-beam-type polarized proton source might be obtained from a vendor or from DoE surplus. Alternatively, Michigan might construct a high intensity polarized source using the ultra-cold atomic beam technique of our Michigan-MIT polarized gas jet for UNK. Either source could produce either $p^+_\uparrow$ or $H^-_\uparrow$.

## PROCEDURE FOR ACCELERATING POLARIZED PROTONS

The change-over from unpolarized to polarized operation would involve the following steps:

a. Adjust the switching magnet to inject polarized rather than unpolarized ions or protons into the main injection line to the LINAC.

b. Measure the polarization at 600 MeV with a carbon target polarimeter and tune the polarized source to maximize the polarization.

c. Turn on the partial Snake in the LEB and then adjust its ramp and the timing of the pulsed quads to maximize the polarization measured in the internal polarimeter.

d. Turn on the two MEB Snakes and then measure the polarization in the MEB 200 GeV internal polarimeter which will probably use Coulomb-Nuclear Interference. [This should have an analyzing power of about 4.6% at $P_\perp^2 = 0.0032\ (\text{GeV}/c)^2$ independent of energy[29].] Adjust all Snake currents together to maximize the polarization.

e. Turn on the six HEB Snakes and then measure the polarization in the HEB internal Coulomb-Nuclear Interference polarimeter. Adjust all Snakes together to maximize the polarization.

f. Turn on the 26 Snakes in 20 TeV Ring number 1 and maximize the polarization measured in the 20 TeV internal polarimeter by varying all 26 x 8 = 208 magnet currents together.

g. Repeat step f for 20 TeV Ring number 2.

h. One might install 2 symmetric Snake Spin Rotators in one or more interaction regions to provide longitudinal polarization.

i. The spin direction should probably be reversed every few minutes to minimize systematic errors. This can probably be done by inducing a spin flip in each Ring using an "RF" Spin Flipper or by using a Snake Spin Rotator at each interaction region.

j. By using the LEB and possibly the MEB as accumulator rings, one should be able to reach full SSC luminosity even with a presently existing 100 $\mu$A atomic-beam-type polarized proton source.

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# APPENDIX B

## (Used with permission of O. Chamberlain)

POLARIZED BEAMS AT SSC
ANN ARBOR, MI 1985

EDITORS:
A. D. KRISCH & A. M. T. LIN
UNIVERSITY OF MICHIGAN
O. CHAMBERLAIN
UNIVERSITY OF CALIFORNIA, BERKELEY

## REPORT OF THE SPIN GROUP

Owen Chamberlain
Lawrence Berkeley Laboratory and Department of Physics
University of California, Berkeley

### INTRODUCTION

A few comments are necessary about how we present our predictions about results. Firstly, we assume luminosity $L = 10^{33}$ cm$^{-2}$sec$^{-1}$, at full energy of 20 TeV, each beam. At half energy we assume half that luminosity. (That is, the luminosity is proportional to beam energy.)

To justify our use of full luminosity for polarized as well as unpolarized beams, we use as our model the booster of the AGS. Present capabilities allow $10^{10}$ polarized protons in the AGS. We are counting on the new accumulator-booster to provide a factor of 20 in intensity. We are also assuming that in the next few years there will be polarized proton sources with 5 times the brightness of present sources. Together, these assumptions allow $10^{12}$ polarized protons in the AGS, enough to provide full luminosity.

Secondly, we have adopted a standard, rather long period of running time for each measurement, namely 100 days, about $10^7$ sec. We imagine such a run would require at least one calendar year.

Thirdly, we assume 71% beam polarization, this being only a small improvement over the 60% that has been used in high-energy polarized beams.

To allow readers to estimate easily the ideally attainable uncertainty in a polarization parameter, one scheme is set out here. As already explained, luminosity times exposure time is assumed to be $10^{33} \times 10^7$ seconds $= 10^{40}$ cm$^{-2}$. With one nanobarn being $10^{-33}$ cm$^2$, we expect $10^7$ events for each 1 nb of cross section.

If the parameter to be measured is A, a one-spin quantity, presumably in a set-up with unpolarized beam hitting polarized target of polarization 71%, then the value of each event is proportional to $\cos^2(\phi)$, $\phi$ being the azimuthal angle, which $\cos^2$ averages to 1/2, so the expected accuracy of the A measurement should be (with $P_{target}$ being 0.71):

$$\Delta A = (10^7 \text{ events})^{-1/2}(1/2)^{-1/2}(0.71)^{-1}(\sigma(\text{nb}))^{-1/2} = \frac{0.00063}{\sqrt{\sigma(\text{nb})}} .$$

If an azimuthally symmetric 2-spin measurement is being made, such as $A_{ll}$, then reactions are equally valuable (regardless of the azimuthal angle involved). Then $A_{ll}$ is defined as

$$A_{ll} \equiv \frac{1}{P_{beam1}} \frac{1}{P_{beam2}} \left( \frac{\sigma_{++} - \sigma_{+-} - \sigma_{-+} + \sigma_{--}}{\sigma_{++} + \sigma_{+-} + \sigma_{-+} + \sigma_{--}} \right) ,$$

where subscripts + (and −) denote + (and −) helicity of the incoming particles in the c.m. system. The statistical uncertainty in $A_{ll}$ is

$$\Delta A_{ll} \equiv \frac{1}{P_{beam1}} \frac{1}{P_{beam2}} \frac{1}{\sqrt{10^7 \text{events}}} \frac{1}{\sqrt{\sigma(\text{nb})}} = \frac{0.00063}{\sqrt{\sigma(\text{nb})}} ,$$

which is, somewhat by chance, the same result we got for $\Delta A$ above.

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CONFERENCE PROCEEDINGS NO. 145
NEW YORK 1986

Of course these are ideal best accuracies. In the real world one will get less accuracy if there is some background that dilutes the effect even after appropriate cuts are made.

The subjects I want to discuss as examples of interesting spin physics are these:

Proton-proton elastic scattering
Polarization of produced hyperons
Supersymmetry as a threshold effect
Quark compositeness

We expect other processes, ones overlooked here, to contain important spin physics in the future.

The proton structure functions are important to know, for they affect the fraction of a proton's polarization that is carried by a typical parton. The structure functions are not directly determinable from QCD; however, once the structure function is measured at low energy let us say, QCD allows one to calculate how the structure functions change with $Q^2$. When, at higher energy, typical partons carry much less of the proton's momentum they also carry less of the proton's spin. When typical values of (Feynman) x are near 0.2, we expect each parton to carry about 20% (at most) of the proton's spin. This amounts to an important dilution of the proton spin when it is viewed at the parton level. This does not cause spin effects to vanish, but it makes them smaller and harder to measure.

## PROTON-PROTON ELASTIC SCATTERING

Proton-proton scattering at high energy has shown unexpectedly high polarization. We have heard preliminary results from Alan Krisch[1] indicating that he expects the analyzing power A to be about $0.24 \pm 0.08$ (the best value as of July 1985) at $p_T^2 = 6.5$, where $p_T$ is the transverse momentum transfer, usually in GeV/c. Since their most spectacular values of A have been at high momentum transfer (high $p_T^2$) they have tried to push their apparatus in that direction. However, the cross section is falling rapidly and they are hard pressed to go farther with present equipment.

As long as proton-proton elastic scattering is thought to be dominated by the pomeron, proton-proton and proton-antiproton interactions can be expected to show nearly identical angular distributions of elastic scattering. The fact that there are significant differences may indicate that the crossing-odd amplitude may be larger than anticipated. Elliot Leader[2] has called this odd amplitude the odderon phenomenon. In tests of the nature of the difference we expect polarization phenomena to play an important role.

One of the proton-proton two-spin parameters, $A_{nn}$, has been measured[3] at 11.75 GeV in an experiment utilizing polarized beam and polarized target. At high momentum transfer, values of $A_{nn}$ of about 50 percent have been obtained. If similar results could be produced at higher energy they could be a serious challenge to QCD, which predicts much smaller polarization numbers.

## POLARIZATION OF PRODUCED HYPERONS

Heller, Overseth, Pondrom et al.[4] have produced $\Lambda$'s by bombarding a beryllium target with 400-GeV protons. When they study the $\Lambda$ decay angles for $\Lambda$'s produced at 0.07 radians they find sizable $\Lambda$ polarization, up to 25 percent. This large polarization appears to vary with $p_T$ but to be rather independent of incident energy. We may hope, then, that this effect may continue to much higher energy.

The mechanism of the $\Lambda$ polarization is not known at the present time. It will be important to follow the effect to the highest energies possible, so that we may reach the realm where QCD is thought to be applicable. Unfortunately, one must work with smaller and smaller cross sections at higher energy.

## SUPERSYMMETRY SEEN AS A THRESHOLD EFFECT INDICATING A NEW PHENOMENON

The onset of production of supersymmetric particles is currently thought to be best seen by missing transverse energy in one, two or more high $p_T$ jet production. However, as known from UA1,[5] there might be serious background problems, for example $W \rightarrow \tau\nu$, heavy flavors etc. near the threshold for such processes. Typically $gg \rightarrow \tilde{g}\ \tilde{g}$ (associated gluino production) $\tilde{g} \rightarrow \tilde{\gamma} + \text{jet}$ ($\tilde{\gamma}$ = photino, presumably stable and non-interacting).

Theoretically $m_{\tilde{g}}$ can be anything from 2 GeV to some TeV. The important point is that these theories, being GUT theories, are characterized by a very large mass scale $M_x \approx 10^{17}$ GeV, and supersymmetry has to be broken at some intermediate scale. There are a number of postulated mechanisms, which lead to quite different predictions for the mass of the super partners of the known gauge particles, leptons and quarks. Whatever the mass scale, there is an invariance principle (i.e. R – invariance) which must be satisfied, so that SuSy particles are produced in association and decay down always to the lightest stable member of the family. This is mostly thought to be a photino, which is basically non interacting in current detectors. (Hence the missing energy signal.)

How does spin physics help in the search for supersymmetric thresholds?

Being a gauge theory, the basic Born processes are characterized by large double helicity asymmetries (see Fig. 1). In the zero-mass limit all SuSy production processes have $\hat{A}_{ll} = -1$. (The caret indicates an asymmetry at the parton level.) Except associated flavor production, which also has $\hat{A}_{ll} = -1$, all non-SuSy parton processes have $\hat{A}_{ll} > 0$ (about 50% at 90° c.m.).

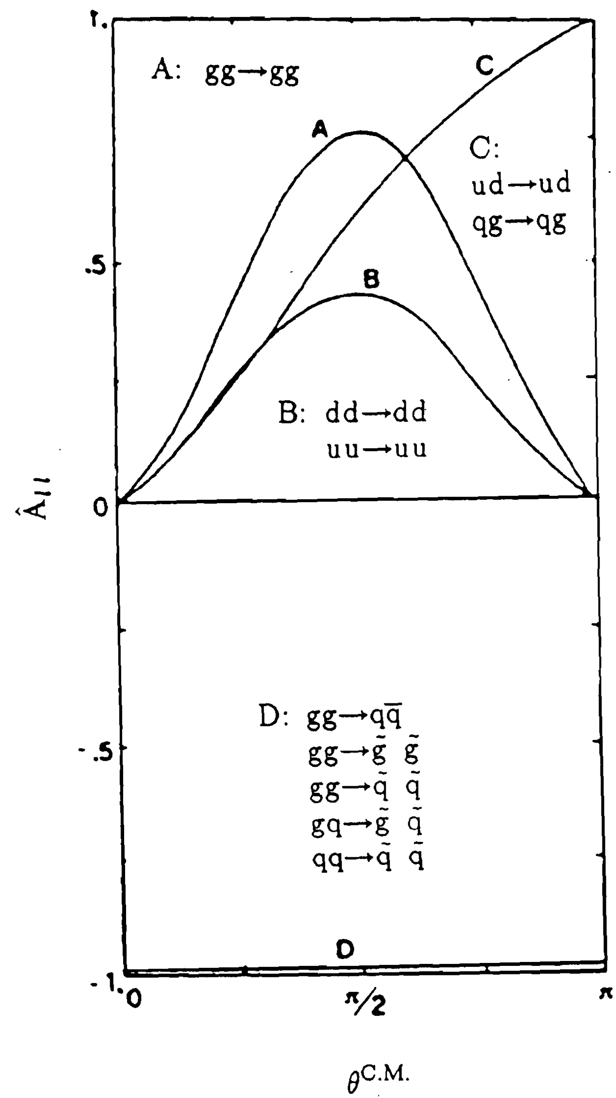



Fig. 1. Partonic helicity asymmetries in the limit of zero gluino and quark masses.

The only non-SuSy background missing-energy events are due to associated heavy-flavor production with subsequent semileptonic decay. This also has $\hat{A}_{ll} = -1$, but the cross section for $gg \rightarrow \tilde{g}\,\tilde{g}$ is typically 20 times larger than for $gg \rightarrow q\bar{q}$ and the semileptonic decay has a branching ratio of only 10 percent, so that this background is only about 0.5 percent to 2 percent, depending on the number of heavy flavors.

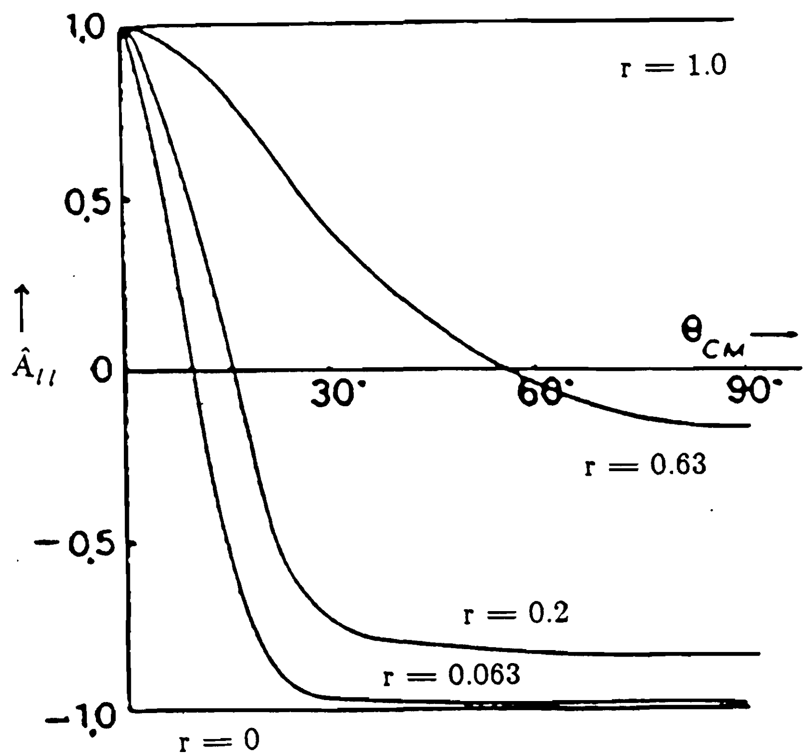



Fig. 2. Partonic helicity asymmetry for $gg \rightarrow \tilde{g}\,\tilde{g}$ for different values of $r = 2M\sqrt{s}$>

Table I. Crude estimate of helicity asymmetries and their uncertainties

| | $\sqrt{s}$ | $r=2m/\sqrt{s}$ | $A_{ll}$ | $\Delta A_{ll}$ |
|---|---|---|---|---|
| $m_{\tilde{g}} = \frac{1}{2}$ TeV | 40 | .025 | −5% | $<10^{-2}$% |
| | 20 | .05 | −5% | .3% |
| | 10 | .1 | −2% | .7% |
| | 5 | .2 | +2% | >20% |
| $m_{\tilde{g}} = 1$ TeV | 40 | .05 | −10% | .5% |
| | 20 | .1 | −10% | 2% |
| | 10 | .2 | −5% | 5% |
| | 5 | .4 | ≈0% | 50% |

As one goes through threshold there are quite dramatic polarization effects. The parameters used here are $R = r^2 = 4M^2/s$ (or $r = 2M/\sqrt{s}$). Notice that $R = r = 1$ at threshold and that smaller R or r values are to be associated with being farther above threshold. Fig. 2 shows the helicity double analyzing power $\hat{A}_{ll}$ for associated production of gluinos by $gg \rightarrow \tilde{g}\,\tilde{g}$ (taken from Craigie et al.),[4] $r = 0.63$ means c.m. energy is 1.6 times threshold. Thus a missing energy signal, coupled with an asymmetry changing sign in some energy region, could be a very definitive way for searching for a supersymmetry threshold. However, the absolute rate is also decisive in showing it is not simply a new heavy flavor threshold.

To get an idea of asymmetries $A_{ll}$ and statistical accuracies $\Delta A_{ll}$ relevant for SSC we present rough estimates for $m_{\tilde{g}} = 0.5$ and 1 TeV and $\sqrt{s}$ varying between 5 and 40 TeV (see table I). We base this on the expected cross sections calculated by Eichten et al.[7] (see Fig. 3) and the asymmetries given by Craigie et al. (see Fig. 4). The problem is that near threshold, e.g. $r = 0.5$, $X_T$ is very large leading to very small cross section. The crude estimates given here should be backed up by more complete calculations. Nevertheless, they show the usefulness of polarization effects as a signature of the opening of a threshold for new physics.

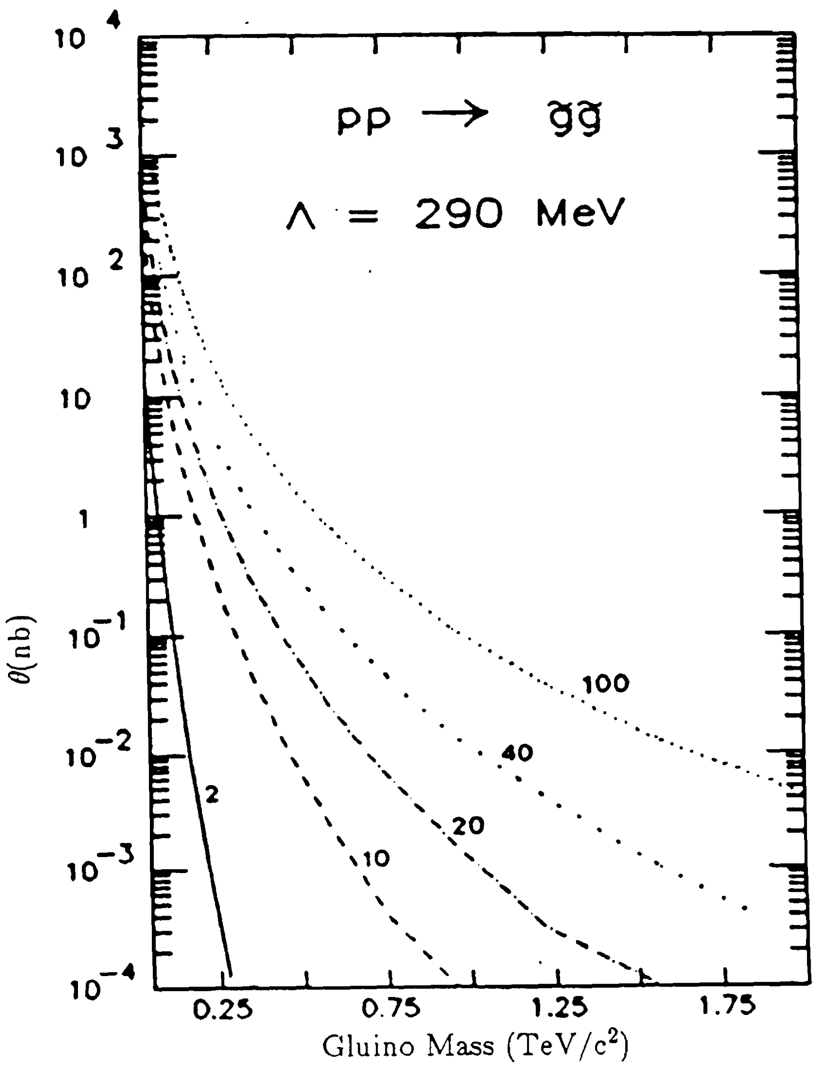
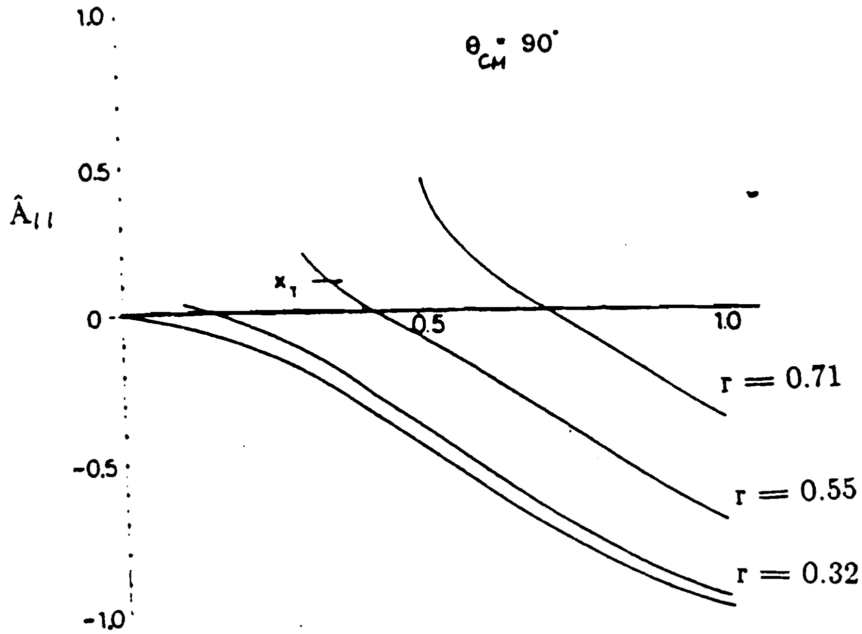



Fig. 3. Cross sections for the reaction $pp \rightarrow \tilde{g}\,\tilde{g}$ + anything as a function of gluino mass for energies $\sqrt{s} = 2$, 10, 20, 40, and 100 TeV.

Fig. 4. Helicity asymmetry pp $\rightarrow \tilde{g}\ \tilde{g}$ X for different values of r plotted against $x_T$ for $\theta_{CM} = 90^\circ$.




## POLARIZATION IN THE SEARCH FOR THE COMPOSITENESS OF QUARKS

In composite models of quarks one has new subprocesses contributing, along with the ordinary partonic subprocesses, that have the promise of showing up as large effects in various hadronic reactions when the scale of compositeness is being approached. However, if there is a new parity-violating effect (models of composite quarks allow for parity violation at the parton level), polarization could help. The parity violating asymmetry is

$$\frac{\sigma(+) - \sigma(-)}{\sigma(+) + \sigma(-)} = \frac{\epsilon}{1+\epsilon}$$

$$\text{where} \qquad \epsilon \approx \frac{t\alpha_t}{\Lambda^2 \alpha_s}$$

and $\Lambda$ is the scale of compositeness, $\alpha_t$ is the effective coupling of the preons and $\alpha_s$ the strong coupling constant. Thus this asymmetry would grow very fast with t and such experiments would be quite sensitive if $\Lambda \approx 4$ TeV).

For a number of reasons it may be important to keep in mind the spin physics that can be done at less than the full SSC energy of 20 TeV, each beam. The accelerator experts report that the depolarizing resonances get stronger at high energy, making it harder to avoid some depolarization during acceleration. Furthermore, the dilution effect is believed to be greater at the highest beam energies.

While the luminosity at 5 TeV will be only about one quarter as large as at 20 TeV, the cross sections will be larger.

In conclusion, there are many ways polarization phenomena are important to observe, to gain a full understanding of physical processes. In fact, the observations are incomplete until spin has been taken into account in the observation. It would be a tragedy if SSC were built in such a way that polarized beams could not be an added feature at some future time.

This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Division of High Energy Physics of the U. S. Department of Energy under contract #DC-AC03-76SF00098.

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# APPENDIX C

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PHYSICS REPORTS (Review Section of Physics Letters) 177, Nos. 5 & 6 (1989) 319–405. North-Holland, Amsterdam

# SPIN EFFECTS AT SUPERCOLLIDER ENERGIES

C. BOURRELY, J. SOFFER

*Centre de Physique Théorique*, CNRS, Luminy, Case 907, F-13288 Marseille Cedex 9, France*

F.M. RENARD

*Laboratoire de Physique Mathématique**, USTL, Place E. Bataillon, F-34060 Montpellier Cedex, France*

P. TAXIL***

*Division TH, CERN, CH-1211 Geneva 23, Switzerland*

Received December 1988

*Contents*:



* Laboratoire propre du CNRS LP 7061.
** Unité associée au CNRS no. 040768.
*** Permanent address: Centre de Physique Théorique, CNRS, Case 907, Luminy, F-13288 Marseille Cedex 9, France.

*Abstract*:
Polarization studies have proven to be relevant at current accelerator energies, providing valuable experimental information in different areas of particle physics, some of which is a real challenge for dynamical theories. The purpose of this review is to answer the question: does hadron supercollider physics need polarized beams? We present in the framework of gauge theories, Standard Model and beyond it, many original calculations of single or double helicity asymmetries for a large number of interesting processes. These results, some of which are spectacular, emphasize the significant advantages of the full use of polarized proton beams for signal detection in the exploration of the 1 TeV scale.

## 1. Introduction

Hopefully there will be several multi-TeV hadronic machines in operation in the next decade. The chances are high that in the United States a Superconducting Super Collider (SSC) with an energy of 20 TeV per beam and a luminosity of $10^{33}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ will be built. Europe is planning a Large Hadron Collider (LHC), to be hosted in the LEP tunnel, with a proton beam energy of 8 TeV or so and a luminosity up to $10^{34}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. There are many fundamental reasons why particle physics needs high energy, high luminosity and why these new hadron colliders will be major research facilities. Within the framework of the Standard Model we still have to discover the Higgs boson, whose mass is unknown, and we must get a physical understanding of why and how the electroweak symmetry is broken. We would like to know if heavier quarks and leptons exist and if there is a deep reason for having a particular number of generations. Although parity violation has been known for many years, an important question remains: is parity violation of the Standard Model a low-energy property of nature? The answer to this question may be given by extending the standard gauge structure, for example by restoring right–left symmetry. Other extensions have also been proposed in the framework of grand unified theories or inspired by superstring models. There is some hope to go beyond the Standard Model and to hit new areas in particle physics where new particles and new interactions would show up. For example, one would like to discover supersymmetry, a further symmetry in nature relating fermion and boson states, or to detect any structure quarks and leptons could have, another attractive possibility.

To open windows for new physics these future machines should be able to search for quite high masses, say in the TeV range, and given the fact that quarks or gluons often carry only a small fraction of the hadron momentum, a beam energy of several TeV is certainly required. Moreover, the cross section for producing a new particle of mass $1\ \mathrm{TeV}/c^2$ is of the order of $10^{-36}\ \mathrm{cm}^2$ or smaller (assuming the interaction coupling constant is of the order of 0.1), so one should achieve a luminosity of $10^{33}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, which will allow one to reach cross sections as small as $10^{-40}\ \mathrm{cm}^2$ with a running time of $10^7$ s/year. Knowing that this interesting physics will lie in small cross sections and that signal detection will be the hardest part of data analysis, further means are needed to disentangle new physics and polarized beams might be one way to do it.

Spin has been shown to be very useful at lower energies [BOU80, YOK80, CRA83, BRO82, MAR84, SER86, MIN88], providing elegant and powerful methods in various instances, some of which are worth recalling:
- the precise measurement of the mass of the upsilon mesons using resonance depolarization of the polarized beam in a $e^+e^-$ storage ring [ART82], a method which was used earlier at Novosibirsk for the phi meson [BUK78];
- the use of the transverse polarization of the beams in a $e^+e^-$ storage ring both at Spear [SCH75] and Petra [ORI79] up to $\sqrt{s} = 30$ GeV to confirm the spin 1/2 nature of the quarks, from the azimuthal $\varphi$

distribution of charged and neutral hadrons in $e^+e^- \to hX$, which has minima for $\varphi = \pm\pi/2$ as shown in fig. 1.1;
- the famous SLAC experiment [PRE78, PRE79] in deep inelastic ep scattering with a polarized electron beam on an unpolarized target to detect a parity violation effect from $\gamma$–Z interference in beautiful agreement with the prediction of the electroweak theory;
- the observation in hadronic collisions of several interesting effects in exclusive reactions at large angles, which are a real challenge for dynamical models, and also of strong polarization effects in inclusive hyperon production growing with transverse momentum.

Concerning this last point, let us recall that in pp elastic scattering at 28 GeV/$c$, the analyzing power $A$ is of the order of 5% in the small-angle region but increases to a much higher positive value for $\theta_{cm} \sim 45°$ as shown in fig. 1.2. This is evidence for the serious need of non-perturbative effects in a kinematic region where perturbative QCD is believed to be relevant [SOF87]. For inclusive hyperon production by unpolarized 400 GeV/$c$ protons, the experimental situation of the transverse polarization of the final baryon in the proton fragmentation region is summarized in fig. 1.3. It is negative for $\Lambda$, $\Xi^0$ and $\Xi^-$, positive for $\Sigma^{\pm}$ and zero for $\bar{\Lambda}$. For illustration we also show, in fig. 1.4, the $\Lambda$ polarization in $K^-p \to \Lambda X$ in the $K^-$ fragmentation region, which is now positive, larger than in the previous case and essentially independent of the incident beam energy. Some qualitative features of these data are consistent with simple semiclassical theoretical ideas [AND83, DEG85], but we are still missing a serious understanding of the subtle dynamical origin of this important phenomenon where experiment is far ahead of theory.

Finally let us mention an unexpected effect for $\pi^0$ production in the central region with a polarized target, where a large transverse spin asymmetry has been observed as shown in fig. 1.5 in $\pi^-p$ and $\pi^-d$ collisions at 40 GeV/$c$, which was first discovered at CERN in pp collisions [ANT80].

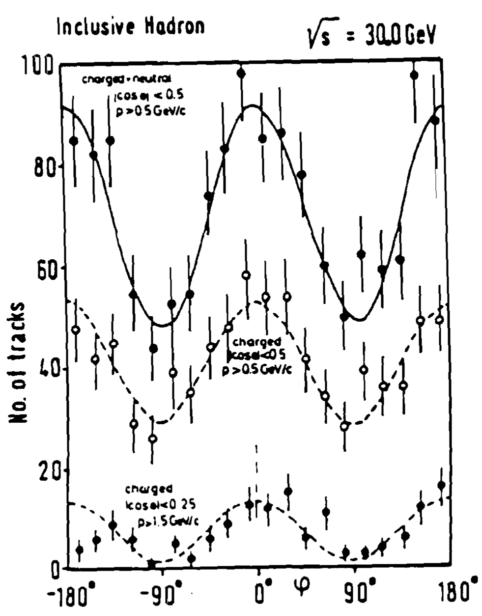


Fig. 1.1. Azimuthal $\phi$ distribution in inclusive $e^+e^-$ hadron production with various cuts at $\sqrt{s} = 30$ GeV, from [ORI79].

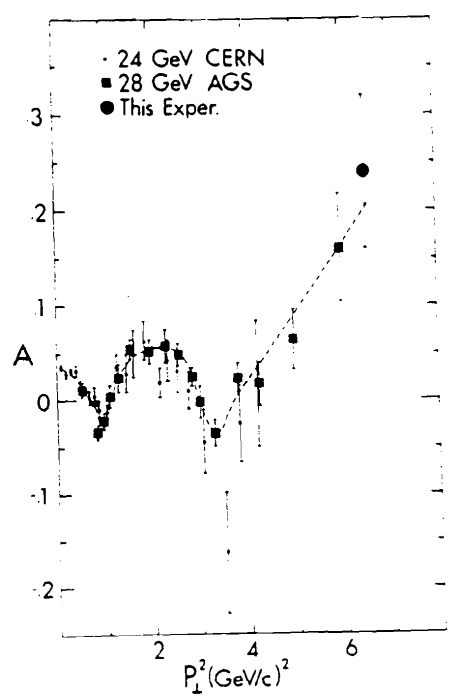


Fig. 1.2. The analyzing power $A$ for pp elastic scattering versus $p_\perp^2$, taken from [CAM85]. The curve is hand-drawn to guide the eye.

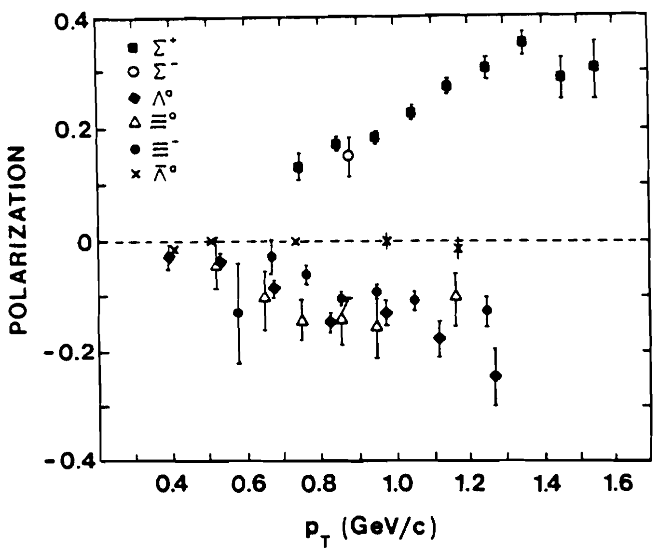


Fig. 1.3. Transverse polarizations of different hyperons produced by 400 GeV/$c$ protons on Be versus $p_T$, taken from [WIL87] and references therein.

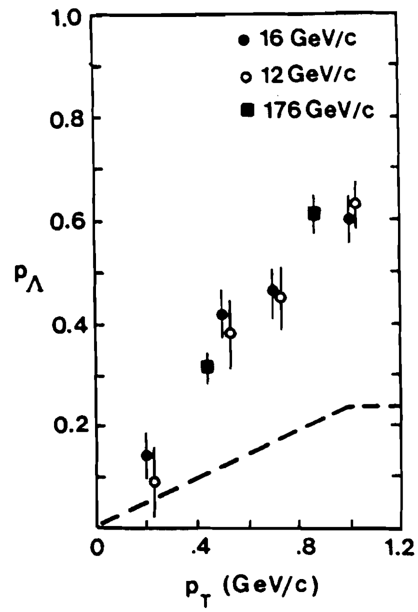


Fig. 1.4. Transverse $\Lambda$ polarization in $K^- p \to \Lambda X$ versus $p_T$ at 12 GeV/$c$ and 16 GeV/$c$, taken from [ARM85], and at 176 GeV/$c$, from [GOU86]. The dashed line shows for comparison the magnitude of $P_\Lambda$ in proton induced reactions.

Clearly, these transverse polarization effects, which make all the excitement in an energy range much below 1 TeV, are too complicated to be explained in terms of lowest-order calculations. However, these calculations are useful to evaluate helicity effects and, as we will see, they are very interesting in the multi-TeV energy range, where life is simpler. There are probably also higher-order effects which may come as surprises but we will restrict our study to the discussion of the lowest-order ones.

In present day hadronic machines there is some real effort to continue the existing experimental programs, both at BNL and Serpukhov, or to undertake new programs at higher energies, like the construction of the polarized proton beam obtained from $\Lambda$ decay at FNAL, which has already

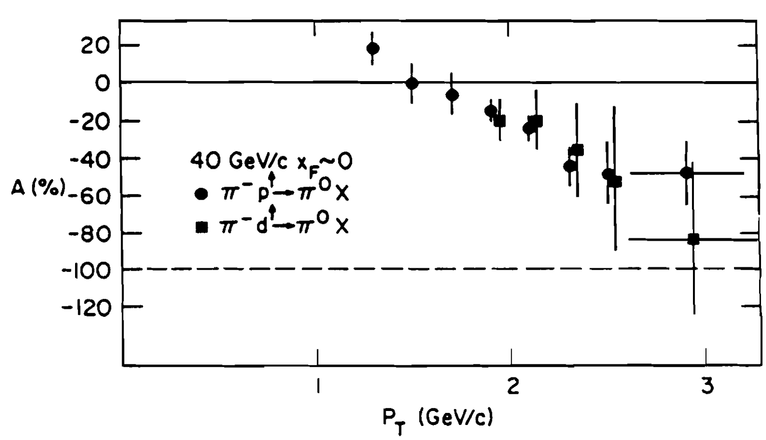


Fig. 1.5. Results on single transverse spin asymmetry versus $p_T$, taken from [VAS88].

produced some data [FNA88], and at CERN the future installation of a polarized gas target by the UA6 collaboration [CER88]. For future machines, polarization is a major concern; in particular HERA will have polarized electrons, which is perhaps one of its most attractive features; SLC will also have polarized electrons and people seem to be convinced now that LEP should have polarized beams [BLO87, ALE88]. This would improve greatly our ability to get an accurate determination of the Standard Model parameters. Moreover, a precise measurement of the left–right helicity asymmetry at the $Z^0$ peak would allow one, through virtual effects, to get some information about the top quark and Higgs boson masses as well as possible manifestations of new physics. Future $e^+e^-$ machines in the TeV energy range are being seriously considered (CLIC at CERN, TLC at SLAC, VLEPP in the USSR) and a recent report [AHN88] shows that the $e^+e^-$ physics community is already aware that "... one should plan for polarization as an integral part of the collider design ...".

The goal of this paper is to show that there are fundamental physics issues which can be illuminated by the use of polarized beams in future hadron colliders, so such an option should be taken seriously in the design of these planned facilities. We will follow the spirit of the work of Eichten, Hinchliffe, Lane and Quigg [EIC84] (henceforth referred to as EHLQ) and we will try to provide reliable estimates of spin asymmetries both for the physics of the Standard Model and for new physics implied by various exciting speculations. We will consider the pp, and not $\bar{p}p$, option, which has the merits on the one hand to reach a higher luminosity and on the other hand to give access to double spin asymmetries, since nobody knows today how to make a multi-TeV polarized $\bar{p}$ beam.

On the contrary, such a proton beam seems feasible and section 2 will be devoted to a short review on this question, where we will recall the essential arguments according to the experts in this field, based in particular on the Siberian Snake concept. In section 3 we will give analytic expressions for a plausible set of unpolarized and polarized parton distributions and we will calculate the parton differential luminosities, which are very useful for a quick estimate of the production rates at supercollider energies. In section 4 we will discuss, as first applications, direct photon production and hadron jet phenomena described in terms of hard scattering constituent interactions. When the subprocess center of mass energy is above 200 GeV or so, weak interactions and consequently large parity violating asymmetries are expected. They will be presented in some detail in section 5 in the framework of the electroweak Standard Model, in particular spin tests in lepton pair, single gauge boson production and pair production of gauge bosons. We will also give some asymmetries involving the production of the most important particle which remains to be found, namely the scalar Higgs boson.

We will then turn to new physics and we will treat in section 6 the minimal extension of the standard model with new quarks, new leptons and new gauge bosons. Compositeness including technicolor will be discussed in section 7, where new couplings among leptons, quarks and vector bosons will be considered, in particular taking into account residual interactions with contact terms. Let us stress already that the chirality structure of such a new interaction is arbitrary: it may well violate parity and this could trigger new spectacular spin effects. In section 8 we will investigate the usefulness of spin as a tool to reveal the existence of SUSY particles. Section 9 will be devoted to a new type of processes, WW collisions, which has a growing interest at supercolliders. We will try to draw some conclusions of our study in section 10.

Finally, the recent results of the EMC experiment [ASH88] on deep inelastic scattering of polarized muons on a polarized target has motivated a large number of theoretical papers on the subject of the proton spin, so we ought to review the present situation. This will be done in appendix A, where we also mention briefly what HERA will miss without proton polarization. This is followed by appendices B to G, where we give several useful but lengthy formulae.

## 2. Technical feasibility of multi-TeV polarized protons

Our purpose is to give a brief summary of reports made by experts in this domain and we just stress what is reasonably expected from the new technical developments [MON84, TER83, COU84].

The present capability to accelerate a polarized proton beam has been proved to a lab energy of 22 GeV/$c$ with a polarization of 46% at the Brookhaven AGS [KRI85], so a big gap has to be bridged in the future to obtain a polarized proton beam with an energy of several TeV. Among the different projects presented in the literature the most probable configuration designed to get a multi-TeV polarized beam contains the following parts: a polarized ion source from which polarized protons are injected into a Linac; the beam is then accelerated and stored in one or two boosters to reach an energy around 1 TeV; next the beam comes into the rings of the main collider, where a new boost produces the final beam energy (fig. 2.1). At first sight this structure looks similar to a standard unpolarized beam accelerator; however, to keep a bunch of protons with all their spins aligned in the same direction is the main difficulty, because there exists a strong tendency for the protons to depolarize when interacting with the electromagnetic fields created by the different magnets installed in an accelerator.

The first component of this chain of devices is an efficient polarized proton source [SCH84]. There exist several types of polarized sources like Lamb shift (metastable) sources, atomic (ground state) sources, ultracold atomic sources and optically pumped sources; all these are currently in use and still

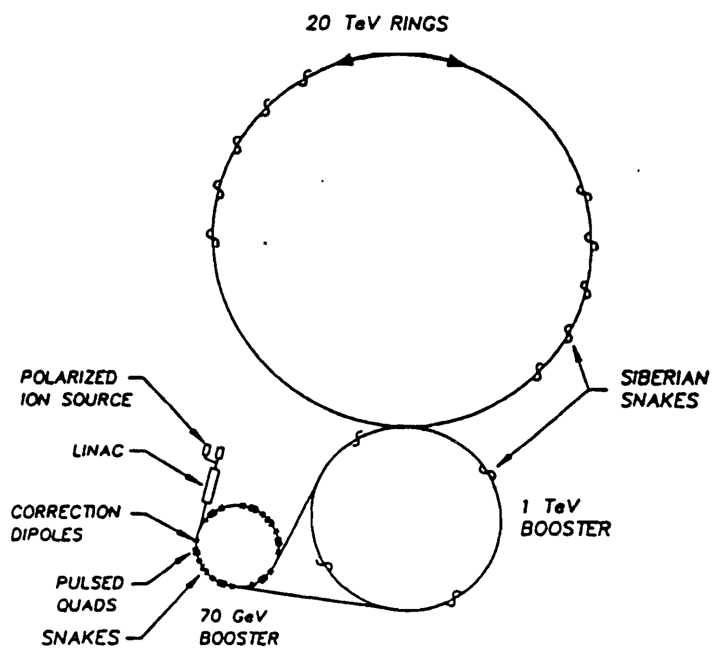


Fig. 2.1. Acceleration of polarized protons at the SSC (not to scale) [KRI85].

under development. It is expected in the near future that $\vec{H}^-$ dc currents of 100 μA will be obtained, as compared with 10 to 20 μA obtainable now. Moreover, a booster such as the one now being constructed at the AGS will increase the useable polarized beam intensity by an additional factor of about 25. High-intensity currents (1 mA) will be necessary to construct a beam of $10^{12}$ polarized protons in order to produce a reasonable total number of events/year for most of the scattering processes of interest.

The main concern when accelerating a polarized beam to high energy is to avoid depolarization resonances, so let us outline how this phenomenon occurs. We consider a circular accelerator in which vertically polarized particles are kept on their orbit by a vertical magnetic field; in that case each particle will precess about the vertical axis, and thus the vertical projection of the spin vector is preserved; as a result no depolarization occurs. However, in order to maintain particles close to the calculated orbit focusing fields are necessary, in particular horizontal magnetic fields; consequently the spin precesses out of the vertical direction, inducing a depolarization. It is shown that depolarization becomes important when the spin precession frequency of the particle is equal to an integer multiple of the frequency with which the particle sees horizontal magnetic fields as it circles the accelerator with the cylotron frequency. If such a condition is realized then a depolarizing resonance occurs; in fact, after each turn a small precession around the horizontal axis adds in phase with those of the previous turns [RUT84].

One distinguishes two major types of depolarizing resonances: the intrinsic depolarization resonances, which are caused by the horizontal magnetic fields of the quadrupole magnets, and the imperfection depolarizing resonances, due to misalignments and imperfect magnets. The number of resonances a particle has to cross in an accelerator of 20 GeV is about 30; this number increases to 200 for an energy up to 100 GeV and in the case of the SSC there will be around 30 000 imperfection depolarizing resonances to correct in each ring!

For low-energy accelerators like the ZGS and the AGS intrinsic resonances are destroyed by the technique of "resonance jumping" using fast quadrupole magnets; in the case of imperfection depolarizing resonances, correction dipole magnets are applied to the beam. All these techniques work well up to energies of 30 GeV; their extension to higher energy seems inappropriate because one has to deal with hundreds of resonances. A solution to the problem of depolarizing resonances was invented by Derbenev and Kondratenko [DER77]; this solution is known as the "Siberian Snake".

The basic idea of a Siberian Snake is to use a string of six to ten magnets which precesses the spin by 180° around the longitudinal direction after one turn around the accelerator and at the same time yields no net orbit deflection (the magnets give an important beam motion so the orbit follows a twisted path like a snake). During the circulation of the beam any spin rotation which occurs after the first turn is then canceled by the identical rotation which occurs during the second turn. There are different possibilities to combine several Siberian Snakes; for instance, one Snake rotates spin by 180° about the longitudinal direction (type I Snake), while another one rotates it by 180° about the horizontal direction (type II Snake). In that case the precession frequency is 1/2, but the equilibrium spin is now up in one half of the accelerator and down in the other, the main advantage of the Siberian Snake technique being that the effect is energy independent. Let us notice that for the SSC a number of 50 Snakes are probably required in each ring to maintain a well-polarized beam. An experimental model of the Siberian Snake is presently being tested at the IUCF proton cooler ring [KRI87, TER88].

In conclusion, accelerating a polarized proton beam up to 20 TeV seems feasible at a reasonable cost (a few percent of the cost of an accelerator with unpolarized beams), provided one confirms that the Siberian Snake technique works experimentally.

## 3. Parton distributions and luminosities

### 3.1. Unpolarized and polarized parton distributions

A high-energy proton beam is an unseparated beam of constituent partons and all fundamental hadronic interactions, which are probed in pp collisions by testing the Standard Model or by producing new particles, involve the collisions of quarks and gluons at short distances. As an example, let us consider the hard scattering hadronic process

$$\mathrm{a} + \mathrm{b} \rightarrow \mathrm{c} \text{ (or jet)} + \mathrm{X}\,, \tag{3.1}$$

which is described in terms of two to two parton subprocesses as shown in fig. 3.1. In the QCD parton model, the corresponding inclusive cross section, provided factorization holds, is given by

$$\mathrm{d}\sigma(\mathrm{a} + \mathrm{b} \rightarrow \mathrm{c} + \mathrm{X}) = \sum_{ij} \frac{1}{1 + \delta_{ij}} \int \mathrm{d}x_\mathrm{a}\, \mathrm{d}x_\mathrm{b}\, [f_i^{(\mathrm{a})}(x_\mathrm{a}, Q^2) f_j^{(\mathrm{b})}(x_\mathrm{b}, Q^2) + (i \leftrightarrow j)]\, \mathrm{d}\hat{\sigma}_{ij}\,. \tag{3.2}$$

The summation runs over all contributing parton configurations; the parton distribution $f_i^{(\mathrm{a})}(x_\mathrm{a}, Q^2)$ is the probability that hadron a contains a parton $i$ carrying a fraction $x_\mathrm{a}$ of the hadron's momentum. It represents the parton flux available in the colliding hadron, which is universal, that is, process independent. Clearly the parton distributions play a crucial role because they allow the connection between hadron–hadron collisions and elementary subprocesses. $\mathrm{d}\hat{\sigma}_{ij}$ is the cross section for the interaction of two partons $i$ and $j$, which can be calculated perturbatively. The total energy of the partons in the subprocess center of mass frame is

$$\sqrt{\hat{s}} = \sqrt{x_\mathrm{a} x_\mathrm{b} s}\,, \tag{3.3}$$

where $\sqrt{s}$ denotes the total center of mass energy of the initial hadrons. Finally $Q^2$, which is defined in terms of the invariants of the subprocess, characterizes the physical momentum scale. The distributions $f_i(x, Q^2)$ are extracted from deep inelastic data at low $Q^2$ and their $Q^2$ dependence, which is logarithmic, is predicted in perturbative QCD by the Altarelli–Parisi equations [ALT77] based on the renormalization group. For supercollider energies the relevant $Q^2$ range is $10^2 < Q^2 < 10^8\ \mathrm{GeV}^2$. The

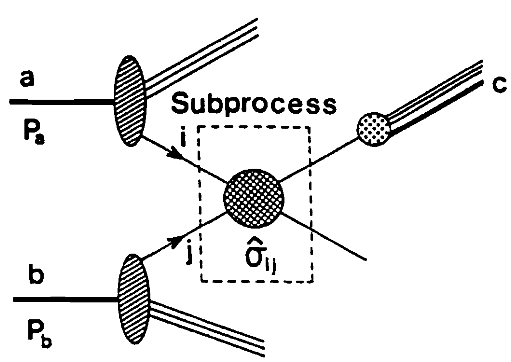


Fig. 3.1. Parton model representation of a hadron–hadron collision at short distances.

## 10. Conclusions

Projects for multi-TeV proton machines are being developed. They are strongly motivated by standard and new physics aspects which are expected to appear in the TeV range. However, these projects have to face an increasing number of difficulties related to the very large number of particles produced during the collision. The analysis of such experiments will require new strategies, new methods, new ideas in order to disentangle the signals hidden in this huge background. This report aimed to answer the question: would polarized proton beams contribute to such a strategy?

We have assumed that longitudinally polarized proton beams will be available in these future hadron colliders such as SSC and LHC. The feasibility is indeed expected from the work of specialized study groups and it is based on the following scheme: a high-intensity polarized source and an acceleration set-up associated with devices such as Siberian Snakes to preserve the beam polarization.

We have chosen a set of spin dependent quark and gluon distributions inside a polarized proton in order to make predictions for hadron helicity asymmetries coming from a given subprocess. In many cases these asymmetries are simply expressed in terms of polarized luminosities multiplied by polarized subprocess asymmetries. The above set of distributions has the appealing feature of being given in terms of a simple analytical form compatible with our present knowledge of the proton structure. New developments initiated by the intriguing result of the EMC experiment might improve our knowledge in this field and yield a more accurate set of distribution functions. In such an event, in order to make new predictions it will be straightforward to reevaluate the polarized luminosities, keeping untouched the subprocess asymmetries established here.

A first application dealt with hard QCD processes which are parity conserving and lead essentially to double helicity asymmetries $A_{LL}$. These $A_{LL}$ were found positive and small for jet and direct photon production and this is a test of QCD and of the spin content of the proton. Jet production will constitute the main part of the background in the search of new particles, so it will be characterized by the smallness of these asymmetries.

Single helicity asymmetries $A_L$ appear with electroweak processes. Because of maximal parity violation, they can be large in some cases, in particular in any subprocess going through a $W^{\pm}$ gauge boson. The $A_L$'s are universal quantities defined by simple combinations of ratios of luminosities. We have stressed that this is one of the best ways to calibrate directly spin dependent distributions in the kinematic range of interest at future supercolliders. On the other hand, there are several interesting channels allowing a test of some crucial features of the Standard Model, especially the structure of the trilinear gauge coupling in boson pair production and the existence of the Higgs produced in association with $W^{\pm}$. Here the information one obtains by means of polarized beams is rather unique.

We have applied the same method in order to characterize features of minimal extensions of the standard electroweak model. In this case also polarization should allow us to characterize immediately the nature of the new gauge boson, $W^{\pm}$ right-handed or $Z'$ associated with a new U(1).

If we turn to genuine new physics let us turn first to compositeness. In the fermion sector it is likely that a residual interaction will involve a specific chiral structure, which will lead to spectacular effects in helicity asymmetries. We have illustrated the occurrence of strong departures from Standard Model predictions in lepton pair production, direct photon production and jet production. In the boson sector, $A_L$ was shown to be able to discriminate between several models which predict anomalous self-boson couplings and which yield the same unpolarized cross sections. Composite partners like an isoscalar Y boson, an excited $W^*$ or techni-rhos will be clearly identified in the same way.

Other exotic partners are those predicted by supersymmetric theories. A negative $A_{LL}$ is a typical feature of jets plus missing energy events coming from the production of squarks and gluinos. Moreover, $A_L$ in slepton pair production and also in neutralino pair production is very sensitive to the mass spectrum of the left- and right-handed scalar partners.

A new class of processes which are accessible at supercollider energies are WW collisions. They have been advertised for the search of a very massive Higgs boson and for studying the behavior of $W_L W_L$

scattering but recognized as rather difficult to extract from the background. Here also polarization will help because of the purely left nature of $W^{\pm}$ exchanges compared to other gauge boson exchanges.

Polarization gives access to new observables $A_L$ and $A_{LL}$, which contain a definite signature of the underlying dynamics. They provide an elegant way to reduce the background and to clarify signals for new physics. Polarized proton beams will undoubtedly be very useful and they may turn out to constitute key tools for the next generation of hadron supercolliders.


## Acknowledgements

The motivation for this review originated at the Workshop on Polarized Beams at SSC (Ann Arbor, June 1985) and it is a pleasure to thank Alan Krisch and Owen Chamberlain who organized this meeting. We also wish to thank Maurice Jacob for his encouragement in undertaking this project and constructive suggestions. Mrs Antoinette Sueur deserves special thanks for her rapid and careful typing of the manuscript.


## Appendices

### *Appendix A. The EMC effect, its various interpretations and consequences*

In the parton model one introduces the spin dependent structure functions defined in terms of quark and antiquark helicity asymmetries as

$$\begin{aligned} g_1^{\mathrm{p}}(x) &= \frac{1}{2} \sum_i e_i^2 [\Delta q_i(x) + \Delta \bar{q}_i(x)] \\ &= \tfrac{1}{18} [4\,\Delta u(x) + 4\,\Delta \bar{u}(x) + \Delta d(x) + \Delta \bar{d}(x) + \Delta s(x) + \Delta \bar{s}(x)] \end{aligned} \tag{A.1}$$

for protons and similarly $g_1^{\mathrm{n}}(x)$ for neutrons, obtained from $g_1^{\mathrm{p}}(x)$ by the substitution $\mathrm{u} \leftrightarrow \mathrm{d}$. The total amount of the proton spin carried by quarks and antiquarks is

$$\Delta \Sigma = \Delta u + \Delta d + \Delta s\,, \tag{A.2}$$

where

$$\Delta q_i \equiv \int_0^1 \mathrm{d}x\, [\Delta q_i(x) + \Delta \bar{q}_i(x)]\,. \tag{A.3}$$

Clearly the gluon helicity asymmetry and parton orbital angular momentum can also contribute to the proton spin with the obvious constraint

$$\tfrac{1}{2} = \tfrac{1}{2}\,\Delta \Sigma + \Delta G + \langle L_z \rangle\,. \tag{A.4}$$

Through the light cone operator product expansion the $\Delta q_i$ are related to the matrix elements of the quark axial-vector currents between longitudinally polarized protons. By making use of the SU(3)

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