Updated

DoE - CH40661 - 1

***Technical Progress Report
Indiana University
High Energy Physics
Task A***

April, 1991 to April, 1992

B. Brabson, R. Crittenden, A. Dzierba,
G. Hanson, H. Martin, T. Marshall, R. Mir,
T. Mouthy, H. Ogren, D. Rust, S. Teige,
D. Zieminska, A. Zieminski

*Department of Physics
Indiana University
Bloomington, IN 47405*

Personnel

The Experimental High energy Physics Group (Task A of the DOE contract) at Indiana University consists of the following:

Faculty : B. Brabson, R. Crittenden, A. Dzierba, G. Hanson, H. J. Martin, H. Ogren and A. Zieminski

Research Physicists : X. Lou, T. Marshall, R. Mir, D. Rust, S. Teige and D. Zieminska

Graduate Students: G. Alvarez, D. Averill(PhD 91), J. Gunter, S. Kartik(PhD 91), R. Li, R. Lindenbusch, C. Murphy, W. Murray(PhD 91), M. Settles, E. Silva and M. Yurko(PhD 1991)

Technical Staff : T. Collins (Engineer/Designer), F. Luehring (Physicist/Programmer), B. Martin (Technician), Alex Zhukovsky (Assistant research Scientist), P. Smith (Electronic Engineer), T. Sulanke (Applications Programmer/Engineer), E. Wente (Assistant Research Scientist)

Secretary : D. Martin

Accountant : S. Snodgrass

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

Experiments

During this reporting period the group has been carrying out programs in several areas. These are presented in approximately chronological order:

- *Stanford Linear Accelerator Lab (CA)*

The group was a collaborator in the Mark II experiment at the SLC and completed analysis on the experiment. Three students completed their theses this reporting period.

- *Fermi National Accelerator Lab (IL)*

The group is the prime mover in (E672), a high mass dimuon experiment which now in its final data collection period. Our group is also a collaborator in the D0 collider experiment which is now preparing for the first data run in 1992.

- *CERN (Geneva, Switzerland)*

The group is a collaborator in the OPAL experiment at LEP which is now taking data. The group also is working on the development of a major offline facility *shift* and on a silicon vertex chamber for 1993.

- *Brookhaven National Laboratory (NY)*

The group is the prime mover in the construction of a major new experiment (E852) in precision meson spectroscopy. A test run is presently underway and data taking will begin in 1993.

- *SSC (TX)*

The group is a prime mover in the tracking design of the SDC experiment. The SDC has completed the Technical Design report. Construction will begin in 1993.

The assignment of personnel to these efforts is shown in Tables 1.1 through 1.4.

Space and Facilities

The group occupies 3,358 sq. ft. of office space and 8,654 sq. ft. of laboratory space (including a hi-bay area) in Swain Hall. The group also has access to the Physics Department machine shop at no cost.

Construction Facilities

The High Energy Physics Group has extensive facilities for constructing detector apparatus. Computer-aided design software is available for electronics and mechanical design. There is an electronics assembly and test laboratory with tools for building printed circuit or wire-wrap devices. Meters, oscilloscopes, and VAXstation computers with CAMAC and FASTBUS interfaces are available for testing electronics and detectors. There are also CAMAC crates linked by serial lines to the VAX 6340 for low data rate tests. There is a departmental machine shop with 5 full time machinists. Other facilities include two wire winders for proportional chambers and a large flat jig table located in a clean room. Also available for detector testing is a large room with access to a truck loading area.

Computing Facilities

The local computing facilities for the Indiana University High Energy Physics group consist of a VAX cluster, three UNIX workstations, and sixteen Macintoshes.

A VAX 6340 and five VAXstations make up the VAXcluster. In April 1992 a VAXstation 4000/60 was added to the cluster. This VAXstation (IND6) has three times the CPU capacity of one of the 6340's four CPU's. It is used primarily as a CPU server for E672, data processing and D0 software development. In February 1992 a 1.4 Gigabyte disk was added to one of the VAXstations bringing the total disk space available to the whole cluster to 7 Gigabytes. The two Exabyte drive tape system is heavily used for processing data from E672, storing Monte Carlo data for D0, and for routine backup. The VAX also has two 9-track tape drives and three laser printers. Through its terminal servers it can be accessed by about 12 terminals, the Macs, and 4 dial-in modems. The VAX can be accessed via internet or serial lines from the Macs, the workstations, and many external computers or via DECnet from HEPnet. We are using nearly 100% of the available CPU

time on the VAX cluster, E672 data analysis and D0 Monte Carlo studies being the primary users.

Two of the VAXstations (IND1 and IND2) are being used for detector hardware development and data acquisition. IND1 is being used by the SDC development group. IND1 has been equipped with a Fastbus interface. The other data acquisition VAXstation, IND2, has a CAMAC interface and its own Exabyte tape drive. It is used with the E852 lead glass detector prototype currently at BNL.

A Silicon Graphics Personal Iris 4D25 workstation is used for online data analysis, running simulations for E852, and will be used for analyzing data offline for this experiment. This workstation has 16 Megabytes of memory, 760 Megabytes of disk storage, and an Exabyte tape drive.

A second IBM RISC System/6000 workstation was delivered in August of 1991. The two IBMs are being used to run simulations and CAD software for SDC development and for computer aided design. One workstation has 32 Megabytes of memory, 640 Megabytes of disk, an Exabyte tape drive, and a CD reader. The second has 64 Megabytes of memory, a 400 Megabyte internal disk, and a 1.4 Gigabyte disk. An Xterminal was purchased in 1991 for use with these machines.

The UNIX workstations are connected to internet allowing remote logins and file transfers between them and many other systems.

A total of sixteen Macs are used by faculty, staff, and graduate students. These Macs are used to run a variety of analysis and word processing programs. They also are used as terminal emulators to connect to the other local computers and computers at various laboratories. Two laser printers are networked to these Macs.

SSC Facilities

We have developed a number of facilities for use in our SSC effort at Indiana University.

- We have modified an assembly area for the construction of a 4 meter long prototype straw module.

- For the tests in this assembly area we have put together gas mixing facilities and have purchased two fast oscilloscopes- a Hewlett Packard 54503A digital oscilloscope with 500 MHz bandwidth, and Textronics 2467B , 400 MHz oscilloscope with enhanced imaging.
- We have also constructed a straw module test stand that will permit simultaneous cosmic ray and high rate source tests. This includes a FASTBUS readout system of up to 64 TDC channels. It is interfaced to a VAX workstation, which is in turn networked to our VAX 6340 mainframe.
- For SSC tracking simulation work we have two IBM 6000 workstations. These are interfaced via Ethernet to the VAX 6340.
- We have a number of software packages that run on the VAX and the IBM to facilitate our interaction with the SDC design and engineering . This includes PRO Engineer, and the finite element analysis program NISA.

Faculty	BNL E852	FNAL E672	FNAL D0	SLC MARK II	CERN OPAL	SSC SDC
B. Brabson	√			√		√
R. Crittenden	√	√				
A. Dzierba	√	√				√
G. Hanson				√	√	√
H. J. Martin		√	√			
H. Ogren				√	√	√
A. Zieminski		√	√			√

Table 1.1

Research Physicists	BNL E852	FNAL E672	FNAL D0	SLC MARK II	CERN OPAL	SSC SDC
J. Li			√			
X. Lou					√	
T. Marshall		√	√			√
R. Mir					√	
T. Mouthuy					√	
D. Rust				√	√	√
S. Teige	√					
D. Zieminska	√		√			√

Table 1.2

Graduate Students	BNL E852	FNAL E672	FNAL D0	SLC MARK II	CERN OPAL	SSC SDC
G. Alvarez			√			
D. Averill				√		
J. Gunter	√					
S. Kartik		√				
R. Li		√				
R. Lindenbusch	√					
W. Murray				√		
C. Murphy			√			
M. Settles					√	
E. Silva					√	
M. Yurko				√		

Table 1.3

Technical Staff	BNL E852	FNAL E672	FNAL D0	SLC MARK II	CERN OPAL	SSC SDC
T. Collins						√
F. Luehring						√
B. Martin						√
A. Zhukovski	√					
P. Smith	√	√				
T. Sulanke	√	√	√		√	
E. Wente						√

Table 1.4

Mark II at the SLC and at PEP

The Mark II Collaboration

LBL-Berkeley-Santa Cruz-Indiana-SLAC-Caltech-Johns Hopkins-Michigan-Hawaii-Colorado.

Indiana Participants

Graduate Students: Mike Yurko, Doris Averill, Bill Murray

PhD Physicists: Bennet Brabson, Gail Hanson, Xinchou Lou, Harold Ogren, David Rust and Arthur Snyder.

Mark II Physics

1989-1991

The Stanford Linear Collider (SLC) provided electron-positron colliding beams with a center-of-mass energy in the region of the Z^0 resonance (91 GeV). In 1989 approximately 500 Z^0 's were produced in the center of mass energy range from 89.2 to 93.0 GeV. The first observations were made of the hadronic decays of the Z^0 . From these data precise measurements of the mass and width of the Z^0 were made and, with the Standard Model partial widths, an upper limit on the number of light neutrino species was found to be three. Several specific decays of the Z^0 were observed including its decay to pairs of leptons, and pairs of bottom quarks. Also, a number of QCD predictions of event shapes, particle inclusive distributions, and numbers of were made at the Z^0 . Mark II data provided several direct comparisons with these QCD predictions. In addition, several searches for new particles were done using the extended kinematic range available at the Z^0 . Specifically, searches were done for the Higgs, for t and b' quarks, for supersymmetric particles, and for neutral heavy leptons, both stable and unstable.

1991-1992

Both the Silicon Strip Vertex Detector (SSVD) and the Drift Chamber Vertex Detector DCVD) were in place during the 1990 running of the Mark II experiment. These chambers enable one to select an enriched B meson sample based on the B's long lifetime.

Recent studies of the $b\bar{b}$ fraction and of the charged multiplicity of $b\bar{b}$ events are reported below.

Detector Upgrades and Improvements

The Mark II detector was the first detector to take data at the SLC. The detector was an upgraded version of the device previously used successfully at the PEP and SPEAR storage rings. The upgrade included a new central drift chamber (Gail Hanson was in charge of construction of the new central drift chamber before moving to Indiana University), a new time-of flight system, a new coil, new endcap electromagnetic calorimeters, and a **new muon facade** extending the coverage for muon detection. In the fall of 1989 both the Silicon Strip Vertex Detector (SSVD) and the Drift Chamber Vertex Detector (DCVD) were installed and contributed to the final Mark II runs of 1990. The SSVD achieved a track resolution of better than $10\ \mu\text{m}$.

Muon Facade Physics

Indiana's major hardware contribution to the detector was the **muon facade** system. This system was a drift tube system sandwiched behind absorber layers of lead and iron. It was completed in the spring of 1989 (including its TDC electronics built by the Michigan group) and by July, 1989 was fully operational. With the muon facade system the angular coverage of the Mark II system was extended from $|\cos \theta| < 0.55$ to $|\cos \theta| < 0.85$. The increased muon coverage improved certain areas of physics accessible to Mark II. The particle searches were improved from added muon coverage. For instance, light quark backgrounds to heavy quark searches using high- p_T leptons were reduced by applying isolation criteria to the leptons. Also, the forward-backward asymmetry of muon tagged quarks provided a method of distinguishing charge- $2/3$ quarks from charge $-1/3$ quarks. The added muon coverage in the forward direction made this a more sensitive measurement.

Muon Facade Hardware

In January of 1990 lead shielding for the facades was added to reduce the few MeV photon background. Lead screens proved effective in protecting the upper facades from photons produced along the beam line. Backgrounds were sufficiently reduced to allow the reconstruction of muons reliably. The resolution achieved was $900\ \mu\text{m}$ in the drift tubes.

Muon Facade Software

Indiana physicists created the data acquisition software for the muon facade drift tube system. Doris Averill and Mike Yurko in collaboration with Gail Hanson and Art Snyder were responsible for this data acquisition and calibration software. Bill Murray and Art Snyder developed the alignment software for muon drift tube system.

The SLC Operation and Mark II Data Collection

The first Z^0 event was recorded in April of 1989. The first 500 Z^0 's were collected during the following 6 month period. The final Mark II runs took data at the Z^0 in January 1990 and in the period from July through November 1990. Both the silicon strip vertex detector (SSVD) and the drift chamber vertex detector (DCVD) were operational during these runs, and therefore, for the 300 Z^0 's collected in 1990.

Experimental Results from Mark II at SLC

The $b\bar{b}$ Fraction in Hadronic Z^0 Decays: The vertex detector systems of the Mark II detector were used to tag $b\bar{b}$ events by requiring the coincidence of three or more tracks with significant impact parameters. This tag was 50% efficient and resulted in a sample of 85% purity. The $b\bar{b}$ fraction, $R_{b\bar{b}} = 0.251 \pm 0.049 \pm 0.030$, presented in Ref. 1 below, is in good agreement with other measurements and the Standard Model prediction.

Charge Multiplicity of $b\bar{b}$ Events: An impact parameter tag was used to select an enriched sample of Z^0 decays to $b\bar{b}$ events. These events were used to measure the difference between the average charged multiplicity of $b\bar{b}$ events and hadronic Z^0 events. This difference is $2.1 \pm 1.8 \pm 0.6$ tracks per event and the total $b\bar{b}$ multiplicity is $23.1 \pm 1.8 \pm 0.6$ tracks per event. Also, the non-leading multiplicity of these events (12.3 tracks per event) supports the hypothesis of flavor independent hadronic fragmentation and gives an average energy fraction of bottom hadrons in Z^0 decay of $\langle x_E \rangle_b = 0.61 \pm 0.10 \pm 0.04$. These results are presented in Ref. 2.

Physics Analysis at Indiana

During the last year three Indiana graduate students have completed analyses of both Z^0 data from SLC and 29 GeV data from PEP. We give a brief summary of the three projects here.

The $Z^0 \rightarrow$ (Heavy Quarks) Fractions at the SLC, Doris Ann Averill, presented November, 1991. Dr. Averill studied the fraction of hadronic Z decays which contain bottom and charm hadrons by searching for isolated leptons. Electrons were identified using both the liquid argon calorimeter and dE/dx in the central drift chamber of the Mark II detector. Muons were detected both in the central muon system and by the muon facade system.

Study of Intermittency in e^+e^- Collisions at $\sqrt{s} = 29$ and 91 GeV, William Norton Murray, October, 1991. Dr. Murray studied intermittency, the fractal-like behavior in rapidity, which has recently been investigated in data from several other experiments (Delphi at the Z^0 , HRS and TASSO at ~ 30 GeV). He was able to compare data at these two energies in the same detector, and to compare these results with existing Monte Carlo models.

Energy-energy Correlations in e^+e^- Annihilation Measured at $E_{cm} = 29$ GeV and M_Z , Michael V.J. Yurko, May 1991. Dr. Yurko completed an energy-energy correlation (EEC) analysis on both SLC and PEP data. The measured EEC is influenced both by the underlying QCD shower structure and by the hadronic fragmentation processes. By comparing data at the two energies with each other and with Monte Carlo models, he critically examined these models and was able to extract values of the strong interaction coupling constant, α_s at each energy.

Summary

The final Mark II data was taken in November, 1990. The total data sample, some 800 Z^0 's, was disappointingly small. The majority of Mark II data analysis has been completed and we are not requesting further research support for this project.

1991-1992 Papers from Mark II work:

1. MEASUREMENT OF THE $b\bar{b}$ FRACTION IN HADRONIC Z^0 DECAYS WITH PRECISION VERTEX DETECTORS, R. G. Jacobsen et al., Phys. Rev. Lett. **67**:3347, 1991.
2. MEASUREMENT OF THE CHARGED MULTIPLICITY OF EVENTS CONTAINING BOTTOM HADRONS AT $E_{cm} = 91$ GEV, B. A. Schumm et al., submitted to Phys. Rev. Lett.

Fermilab Experiment E672: Hadronic States Produced in Association with High-mass Dimuons

Overview of the Experiment

Collaboration

Caltech-Fermilab-UIC-Indiana-Louisville-Michigan(Flint)-Serpukhov
Spokesperson: A. Zieminski

E672 Indiana participants in 1991/92

PhD physicists: R. Crittenden, A. Dzierba, T. Marshall, J. Martin, A. Zieminski
Visitor from the Moscow State U. A. Gribushin
Tech. experts: P. Smith, T. Sulanke
Grad. Stud. S. Kartik, R. Li
Summer Student: M. Knudsen

Physics goals

This is an open-geometry dimuon experiment, the aim of which is to study hadronic processes yielding high-mass dimuons (the trigger) and associated particles using proton and pion beams on nuclear targets at beam energies up to 800 GeV/c. The specific goals, which all are related to experimental tests of Quantum Chromodynamics, include:

- general properties of the production of vector mesons (ρ/ω , ϕ and J/ψ)
 - total and differential cross sections
 - production of associated charged and neutral particles
 - dependence on the inelasticity of the collision
 - the A-dependence
- the hadronic production of χ states by observing their radiative decay into $J/\psi + \gamma$
- a search for b-quark decays to J/ψ and double semileptonic $B\bar{B}$ decays to dimuons.

Apparatus

The layout of the combined E672 and E706 experiment is shown in Fig 1. The E706 detector contains a liquid argon calorimeter (LAC), a charged particle spectrometer including silicon-strip detectors (SSDs - 13 planes), proportional wire chambers (PWCs),

straw drift tubes, and a forward calorimeter. The E672 dimuon detector consists of a toroid magnet, proportional wire chambers downstream and upstream of the magnet, scintillator hodoscopes, pretrigger and trigger processor modules. The output of all detectors are available to both experiments.

Data collected in 1990 and 1991:

Events selected by E672 and E706 triggers, containing information from the entire E672/E706 spectrometer, were written into joint EXABYTE tapes. Our 15.5 M triggers represented 17% of the total number of triggers recorded on over 1500 EXABYTE tapes.

Data processing is being done on the IU VAX 6340 computer. First we extracted E672 events from the common E672/E706 EXABYTE tapes. Secondly, we processed them through the muon reconstruction program. We find that 15% of the original dimuon triggers end up as good DST events with two muons linked through the MUON-PWC-SSD system. The program to reconstruct tracks from the combined E672/E706 spectrometer, written by H.J. Martin, has been considerably improved by the author since 1990 (multiple vertices, efficiency, speed, handling of large multiplicity events).

The processing of the 1990 data reconstruction is completed. It required over 8,000h of CPU (4.4 Mips). However, we intend to process selected events once more with an improved algorithm. The processing of the 1991 data is 50% done. It has taken so far 12,000h of CPU on the IU VAX Cluster and 6,000h on the Fermilab Cluster. We intend to complete all data processing by the end of 1992.

The opposite charge muon pair mass spectra for the entire mass range and in the J/ψ region are shown in Fig. 2a and 2b, respectively. Clear peaks corresponding to the production of vector meson ρ/ω , ϕ , and J/ψ are seen. There are 35K ρ/ω 's 6K ϕ 's and 12K J/ψ 's in the data sample. The J/ψ mass resolution is 65 MeV. The vertex distribution for the J/ψ events is shown in Fig. 3. The analysis of the data is in progress.

Analysis of data taken during the 1988 and 1990 runs

We published two papers, based on our limited statistics 1987/8 data.

- (a) the A-dependence of J/ψ production (PRD 141, 1 (1990).)

- (b) Properties of J/ψ production in π -Be and p-Be collisions.
(Fermilab preprint PUB-91/62-E)

Results from the 1990 run have been presented at five international conferences (four talks by the IU collaborators) and published in the conference proceedings. Preliminary physics results obtained so far include:

- (a) differential and total cross sections, A-dependence and event inelasticity dependence for vector mesons: ρ/ω , ϕ , J/ψ and ψ' (see Figure 4).
- (b) Evidence for a χ e^+e^- system with a mass resolution better than 10 MeV (see Fig. 5). There are approximately 70 ± 15 χ events in the sample. We find that $44 \pm 9\%$ of observed J/ψ 's come from χ states decays. The relative production rates for χ_1 and χ_2 states is 0.8 ± 0.4 . E672 is the second successful experiment with sufficient mass resolution to separate production of the two χ states. We expect to increase the statistics of this analysis by at least 50% once the missing sample of the data is processed.
- (c) Evidence for a χ signal in the $J/\psi + \gamma$ system (see Fig. 6). An asymmetry cut of 0.8 for the difference in the lab energies of J/ψ and a γ was essential to obtain the signal. The energies of γ 's accepted by the cut are about 15 GeV. We need to do much more Monte Carlo studies to improve the resolution and to tune the cuts. We hope to lower the gamma energy threshold to 8 GeV. This would increase our χ signal statistics to approximately 500 events.
- (d) Search for B's in the J/ψ decay mode
Several multivertex findings algorithms were developed. Among 12000 J/ψ events analyzed there are 78 events with J/ψ originating from a well separated (3σ) secondary vertex, somewhat more than predicted by our Monte Carlo for J/ψ 's from secondary interactions (55). Eight of the secondary vertices are outside the target region (Figs. 7 and 8).

We have also tried to look for exclusive B decay modes using J/ψ from secondary vertices and additional cuts on charged tracks to select kaons. The J/ψ K and J/ψ K* invariant mass distribution, shown in Fig. 9 shows a clear agglomeration of six events around the B-meson mass.

The 1991 Fixed Target run at Fermilab

This was the third and last run of E672. The run started in July and ended January 8, 1992. We were in the data taking mode from August 15. The run was a great success. We took data with 530 GeV/c and 800 GeV/c protons incident on H, Be and Cu targets. One week was devoted to negative 530 GeV/c beam running. We collected over 10 million E672 triggers corresponding to the total integrated luminosity of 15 pb^{-1} . The corresponding numbers for the 1990 π^- run are: 5.5 M triggers and 8 pb^{-1} .

Five members of the IU group actively participated in the run. A. Zieminski spent extended periods of time at Fermilab, supervising the running of the experiment. R. Li moved permanently to Fermilab and was in charge of the experiment whenever the spokesman was out of town. A. Gribushin, a visitor from Moscow State, coded data extraction and scaler analysis programs. He spent four months at the experiment. J. Martin provided a monitoring and tracking software packages. He also commuted weekly to Fermilab to monitor the quality of the data and to address off-line software needs of the experiment. T. Marshall was in charge of the gas system.

Publications and Theses

Published papers in 1991:

1. V. Abramov et al., "Properties of J/ψ production in π -Be and p-Be collisions at 530 GeV/c", Fermilab PUB-91/62-E.

Invited and review talks published in the Conference proceedings

1. A. Zieminski, et al., Intersections between Particle and Nuclear Physics, Tucson, AZ; May 1991; Proceedings, p. 891.
2. R. Li, et al., DPF Meeting, Vancouver; Aug. 1991; to be published in the Proceedings.
3. R. Li, et al., XXVIII Rencontre de Moriond; Mar. 1992; Proceedings - Fermilab preprint, Fermilab-Conf-89/151-E.
4. A. Zieminski, Penn State Workshop on Nuclear Chromodynamics, Mar. 1992.

MS and PhD Theses

1. S. Kartik (Indiana, A. Dzierba) - completed (1987 data)
2. R. Li (Indiana, H. Martin) - in progress (1990 data)
3. R. Jesik (UIC, S. Margulies) - in progress (1990 data)
4. F. Vaca (UIC, S. Margulies) - in progress (1991 data)

The E672/E706 Apparatus

Figure 1

$\mu^+\mu^-$ invariant mass distribution showing vector meson resonances

Figure 2a

$\mu^+\mu^-$ invariant mass (12000 J/ψ s)

Figure 2b

Dimuon production vertex Z position

Figure 3

We find no statistically significant dependence of α on x_F or p_T .

Figure 4

χ signal using photon converted electron pairs

Figure 5

χ signal using photons found in the LAC

Figure 6

B candidate vertex Z position distributions

Figure 7

Gap Vertex Z Distribution

Figure 8

$J/\psi K, K^*$ invariant mass (very preliminary)

Figure 9

Experiment: FNAL E740 (D0)

Indiana Physicists

Faculty: H.J. Martin, A. Zieminski (IU Contact Person)

Staff Physicists: T. Marshall, D. Zieminska

Postdoc: Jia Li (until February 1992)

Graduate students: Gene Alvarez, Chris Murphy

Overview

D0 is a second generation detector facility at the Fermilab Collider. The experiment is designed to complement the CDF detector with superior coverage and energy resolution for studying jets and leptons emerging from the $p\bar{p}$ collisions. The physics goals of the D0 experiment include the search for the top quark and other new particles and phenomena, and will include precision studies of the W and Z bosons to look for possible deviations from the standard model predictions.

The D0 detector is now rolled into the collision hall and undergoes testing. The collaboration involves more than 300 physicists from the US and abroad. The effort is divided among six major areas of detector instrumentation: central detector, calorimetry, muon detector, electronics, data acquisition and on-line and off-line software. Indiana has been a member of the collaboration since the Fall of 1985. The Indiana participation in D0 has significantly increased in 1992, as a result of completion of the fixed target experiment E672. Our efforts have concentrated on the following areas:

1. Commissioning of the Muon System
2. Cosmic ray scintillator readout
3. Offline Reconstruction
4. Physics Analysis Programs
5. Manpower for Running Shifts
6. D0 Upgrade

1. Muon Detection System

The muon detection system for D0 will have better detection performance than other existing hadron colliders, with respect to both hadron attenuation length and position resolution.

The muon detection system consists of three shells of drift tube chambers completely surrounding the tracking and calorimeter modules of the detector. The tubes have a rectangular cross section (2" x 4") and are between 10 and 20 feet in length. The first shell (A) consists of four planes of drift tubes. The A shell is enclosed by large steel central end toroids. The next shells, B and C, each consist of 3 layers and cover the outside of the steel. These shells are separated by about one meter. The three shells and toroids provide a spectrometer for detecting and measuring the momentum of muons produced in the collision. There is a total of 164 chambers consisting of 12,000 drift cells in this part of the wide angle muon system (WAMUS).

Muons passing through the three shells in the very forward directions (from 12 degrees down to 3 degrees from the beams) are detected and measured with the small angle muon system (SAMUS). The 6 SAMUS chambers each consist of 3 crossed planes of 1 inch diameter drift tubes. There is a total of 6000 tubes in the forward region.

Tom Marshall and Jia Li have been involved in all aspects of constructing of the muon detector. Tom has been in charge of the commissioning of the muon system since 1988. Last year much of Tom Marshall's effort has been dedicated to the final commissioning of the D0 muon detection system in preparation for the first physics run. Tom had developed techniques for repairing and/or replacing failing wires in the muon drift chambers.

2. Cosmic Ray Scintillator Boards

Tom and Jia were responsible for the commissioning of the electronics for the cosmic ray veto scintillator hodoscope. These circuits reside with the muon chamber electronics and handle all signals and logic for the cosmic ceiling hodoscope. Input and output for these circuits is done through the muon system. The board also provides latches, analogs and times of arrival for every photomultiplier input. It must be sensitive to signals only 3 mV

in amplitude and 5 nanoseconds wide. The system has been installed for use with the overall muon data acquisition system.

3. Offline reconstruction and data analysis

Indiana physicists have contributed to the offline reconstruction of the Central Detector (CD) data, muon reconstruction, di-lepton analysis program and trigger studies.

(a) VEES: package for finding secondary vertices

We have been involved in the CD track finding and fitting since we joined the collaboration in 1985. Recently, we developed a program for finding and fitting secondary vertices (VEES) using reconstructed tracks. Since the D0 detector does not measure momenta of charged particles we use the information on the energy deposited in the calorimeter cells along the path of a track. We investigate the feasibility of using K_S decays to calibrate the response of the hadronic calorimeter to low energy mesons. Members of Indiana group involved in this work are Daria Zieminska and graduate students Chris Murphy and Gene Alvarez.

(b) Muon Reconstruction

Work on the muon reconstruction is done in collaboration with the group from the Northern Illinois University. We have undertaken the reconstruction of muon tracks in the overlapping region between the wide and small angle muon systems (Daria Zieminska). Chris Murphy has done a study of vernier pad resolution and provided the appropriate part of the muon calibration program.

(c) DILBOSON: package for studying decays $\text{boson} \rightarrow l^+l^-$

We have set up a package DILBOSON for analysis of vector boson decays to lepton pairs. It includes di-lepton mass constrained fitting and a study of CD tracking and calorimeter data for events containing successfully reconstructed vector bosons. (Daria Zieminska, Chris Murphy). This package, together with VEES, is being used to study the production of J/ψ and associated particles.

(d) Level 1 and Level 2 trigger studies

Andrzej Zieminski and graduate students have carried out Level 1 and Level 2 trigger studies. They verified the validity of the shower library approximation for trigger analysis. At present Andrzej is studying effects of electronic noise on trigger rates.

4. Physics Analysis

Indiana group has taken on a major analysis project: the inclusive production of the J/ψ meson and search for exclusive channels, $B_0 \rightarrow J/\psi + K_S$ and $\chi \rightarrow J/\psi + \gamma$. We are involved in various aspects of the J/ψ production and its reconstruction through the $\mu^+\mu^-$ channel.

The anticipated topic of C. Murphy's thesis is "Study of inclusive production of J/ψ (in $\mu^+\mu^-$ channel) at D0". The anticipated topic of G. Alvarez's thesis is "Study of $J/\psi \rightarrow \mu\mu$ and associated particles (K_S, γ)". We should stress that the J/ψ production was also the main physics focus of the E672 experiment.

5. Running Shifts

We are taking regular shifts with the muon group and with the trigger group. Tom provided a cosmic ray scintillator trigger for the forward detectors for cosmic ray runs.

6. D0 Upgrade

A major goal for the Fermilab Tevatron collider program in the 1990's is the discovery of the top quark. To help reach this goal there will be an upgrade of the collider to higher luminosities, which will require an increased number of beam bunches in the ring resulting in a reduced time between beam crossings.

This new environment will require major upgrades of the D0 detector, which are planned for 1995. The upgrade includes addition of a central field surrounding improved tracking consisting of scintillating fibers and a silicon vertex detector. These improvements will allow the study of B-physics to be an important added ingredient to the D0 physics program. A large fraction (50%) of muons from B decays is expected to go through the

SAMUS detector. All of this puts strong demands on the SAMUS trigger to sort out forward forward going muons with a high efficiency.

SAMUS will use two triggering schemes. The first will use narrow one dimensional strips in x and y projections to give momentum information at the Level 1 trigger. A second trigger requires coarser x-y-u coincidences. But both triggers will often be fooled by the large background rate of low energy hadrons. Then the Level 2 trigger will be overwhelmed trying to sort through all the x-y-u combinations. What is needed is another trigger element to locate the true muon location in 3 dimensions.

A conclusion of the D0 upgrade proposal is that in order to cope with the expected high occupancies in the SAMUS chambers, additional wire proportional chambers with cathode pad readout will be added between the B and C layers to provide space points to aid in triggering. The geometric arrangement of the pad matrix will be determined by the granularity used in the SAMUS trigger scheme and the occupancy of each region.

Tom Marshall was responsible for the forward muon trigger section of the D0 upgrade proposal.

OPAL EXPERIMENT AT CERN

1. Overview of OPAL Detector and Physics

The OPAL detector has been running at LEP at CERN since August, 1989. About 500K hadronic events have been recorded at energies at or near the Z^0 resonance peak, about 350K of these from the 1991 LEP run. The OPAL collaboration has published or submitted over 50 papers reporting results on the Z^0 mass and width, electroweak physics, QCD physics, heavy flavour physics, and new particle searches. A list of OPAL publications is included. The OPAL detector was upgraded with a new silicon microvertex detector for the 1991 LEP run. This detector works well and will continue to collect data during the 1992 LEP run, which is just beginning. We expect to collect at least 700K hadronic Z^0 events during this run.

Physics at LEP

In the energy range accessible at LEP, the mechanisms by which symmetries are broken at present energies should manifest themselves. Among the central physics issues are the study of the Z and W , the determination of their exact masses and widths, and couplings to leptons and quarks. With the energy upgrade of LEP200 an even richer physics region above W^+W^- threshold will open up. It is clear that the focus of the highest energy e^+e^- physics will remain in Europe for many years.

The addition of a silicon microvertex detector to OPAL, with a new beam pipe of radius 5.5 cm, improved the impact parameter resolution by more than a factor of two, to a high-momentum plateau value of about 18 μm . There are about 200K $b\bar{b}$ events per 10^6 hadronic Z^0 events. With the microvertex detector, we are able to tag $b\bar{b}$ events with high efficiency and purity. So far, we are using data taken with the new detector to make improved measurements of τ and average B lifetimes. We are beginning to make semi-exclusive and exclusive measurements of B decays and expect eventually to measure $B_s^0\bar{B}_s^0$ mixing directly.

The OPAL Collaboration

The institutions participating in the OPAL experiment are:

University of Birmingham, UK
Università di Bologna and INFN
Universität Bonn
University of British Columbia
Brunel University, UK
University of California, Riverside
Cavendish Laboratory, Cambridge, UK
Carleton University
Centre for Research in Particle Physics, Carleton University
CERN
University of Chicago
Universität Hamburg/DESY
Albert Ludwigs Universität, Freiburg
Universität Heidelberg
Indiana University
Queen Mary and Westfield College, University of London
Birkbeck College, London
University College London
The University, Manchester
University of Maryland
Université de Montréal
Herzberg Institute of Astrophysics, Ottawa
Rutherford Appleton Laboratory
CEN Saclay
Technion - Israel Institute of Technology
Tel Aviv University
International Centre for Elementary Particle Physics and Dept. of Physics,
University of Tokyo and Kobe University
University of Victoria
Weizmann Institute of Science

Indiana University joined OPAL in June, 1990, at about the same time as the University of British Columbia and the University of Victoria.

The OPAL Detector

The OPAL detector is a general purpose detector designed for e^+e^- physics at the Z boson resonance. The detector is shown schematically in Fig.1. The detector consists of a central tracking detector in a solenoidal magnet, surrounded by a time-of-flight counter array, a lead-glass electromagnetic calorimeter with a presampler, an instrumented magnet return yoke serving as a hadron calorimeter, four layers of outer muon chambers, and an endcap system that includes a small-angle forward detector.

The central detector consists of a system of tracking chambers inside a 0.435 Tesla solenoidal magnetic volume. The central tracking detector consists of a precision vertex chamber, a large volume "jet" chamber, and a chamber for tracking in the $r-\theta$ dimension (the coordinate system is defined with z along the beam axis, and θ and ϕ the polar and azimuthal angles). The main tracking is done with the jet chamber, a drift chamber of approximately four meters length and two meters radius with 159 layers of sense wires and having 24 sectors in ϕ . The region of tracking registering a minimum of 40 wires covers approximately $|\cos\theta| \leq 0.94$. Integrated charges are measured at both ends of the wires and used for determining the position along the wire and for energy loss dE/dx for particle identification.

The electromagnetic calorimeter consists of an array of lead glass elements for detection of electrons and photons and is mounted around the solenoid, covering nearly the full solid angle. The electromagnetic calorimeter consists of a cylindrical array of 9,440 lead glass blocks of 24.6 radiation lengths thickness covering the range $|\cos\theta| \leq 0.82$, and 2,264 lead glass blocks of 20 radiation lengths thickness in the endcaps covering the region between $0.81 < |\cos\theta| \leq 0.98$. Each block subtends a solid angle of approximately $40 \times 40 \text{ mrad}^2$ and projects towards a point near the interaction point in the barrel region and along the beam direction in the endcaps. The two sections of the electromagnetic calorimeter together cover 98% of the solid angle.

Located radially outside the presampler chamber of the electromagnetic calorimeter, the time-of-flight system covers the barrel region of $|\cos\theta| \leq 0.82$. It consists of 160 scintillator bars, 6.8 m long and 45 mm thick, located at a radius of 2.4 m. The hadron calorimeter is of the iron-scintillator sandwich type, with the iron of the

calorimeter serving as the return yoke for the magnet. A system of drift chambers for the detection and identification of muons covers the full solid angle outside the return yoke.

The forward detector includes a luminosity monitor and an electromagnetic calorimeter system for the study of 2γ processes.

A two-layer silicon microvertex detector, along with a new 1.5 mm thick and 5.5 cm radius beryllium beam pipe, was installed inside the OPAL detector for the 1991 LEP run. The silicon microvertex detector is shown schematically in Fig.2. This device consists of 75 sensitive single-sided silicon strip wafers. The silicon strip wafers are of 300 μm thickness and 25 μm pitch. The silicon strips are AC-coupled to the aluminum readout strips. The signal is read out every other strip using MX5 microplex chips, developed at the Rutherford Laboratory. Three silicon wafers each 6.0 cm long are bonded together to form a ladder. The first layer contains 11 ladders and is positioned at radius 6.0 cm. The second layer lies at a radius of 7.5 cm and consists of 14 ladders. The silicon microvertex detector covers the area $30^\circ \leq |\theta| \leq 150^\circ$. Figure 3 shows the impact parameter distribution obtained for $\mu^+\mu^-$ events with the new silicon microvertex detector, compared with the distribution without the microvertex detector.

2. Recent Results from OPAL

The results from OPAL during the last year center around four major topics:

- Measurements of Electroweak Parameters
- QCD Physics
- Heavy Flavour Physics
- Searches for New Particles.

OPAL has analyzed numerous topics. Below we shall concentrate only on some highlights of the analyses. Further information can be obtained from the reference list of the OPAL publications.

Measurements of Electroweak Parameters

During 1991 OPAL continued to run both on the Z^0 peak and at energies away from the peak so as to continue the scan of the peak. Using the data from 1989 and 1990, the four LEP experiments published a joint paper (Ref. 5) on the electroweak parameters of the Z^0 resonance. The results were:

$$M_Z = 91.175 \pm 0.021 \text{ GeV}$$

$$\Gamma_Z = 2.487 \pm 0.010 \text{ GeV}.$$

The common systematic errors of the four experiments are 20 MeV for M_Z and 5 MeV for Γ_Z ; these are due to energy uncertainties of LEP. Recently, due to efforts of physicists in OPAL, asymmetric effects on the LEP energy at the four interaction points due to misalignment of the rf cavities at the higher of the two rf frequencies were discovered. Until these are better understood, more precise measurements of M_Z including 1991 data cannot be given. The effects of these asymmetries on the widths are small, however, and an updated value of $2.499 \pm 0.007 \text{ GeV}$ was recently reported.*

The hadronic peak cross section was measured to be:

$$\sigma_{had}^0 = 41.11 \pm 0.20 \text{ nb}.$$

The partial widths of the Z^0 were measured to be:

$$\Gamma_{had} = 1.744 \pm 0.008 \text{ GeV}$$

$$\Gamma_{e^+e^-} = 83.45 \pm 0.40 \text{ MeV}$$

$$\Gamma_{\mu^+\mu^-} = 83.6 \pm 0.6 \text{ MeV}$$

$$\Gamma_{\tau^+\tau^-} = 83.6 \pm 0.7 \text{ MeV}$$

* Including preliminary analyses of 1991 data, as presented by D. Schaile, "Tests of the Standard Model at LEP," La Thuile, 8-14 March, 1992. The parameters reported in the rest of this subsection are also from this talk.

$$\Gamma_{l+l-} = 83.51 \pm 0.33 \text{ MeV}.$$

The Z^0 partial width to invisible final states, Γ_{inv} , is defined as

$$\Gamma_{inv} = \Gamma_Z - \Gamma_{had} - 3 \Gamma_{l+l-}.$$

However, the ratio $\Gamma_{inv}/\Gamma_{l+l-}$ is extracted using

$$\Gamma_{inv}/\Gamma_{l+l-} = \sqrt{\frac{12\pi R_{l+l-}}{M_Z^2 \sigma_{had}^0}} - R_{l+l-} - 3,$$

where $R_{l+l-} \equiv \Gamma_{had}/\Gamma_{l+l-}$. The measurement of $\Gamma_{inv}/\Gamma_{l+l-}$ can thus be used to determine the number of light neutrino generations:

$$N_V = 3.04 \pm 0.05,$$

where the quoted error includes allowing the top mass to vary from 90 to 200 GeV and 0.02 coming from the common theoretical uncertainty in the luminosity determination.

QCD Physics

OPAL has determined the value of the strong coupling constant, $\alpha_S(M_{Z0})$, from a study of 15 different observables in hadronic Z^0 and τ decays (Ref. 3). The study includes global event shape variables, jet production rates, energy correlations, the Z^0 line shape and decay asymmetries, and the hadronic branching fraction of τ -leptons. The results are summarized in Fig.4. Differences between the α_S values from the different observables can be consistently attributed to unknown higher order contributions to the $O(\alpha_S^2)$ calculations. These uncertainties may be parametrized by variations of the renormalization scale and of the parton virtuality to which the data are corrected, separately for each observable, resulting in a consistent description of the event shapes, jet rates, and energy correlations with the value $\alpha_S(M_{Z0}) = 0.122^{+0.006}_{-0.005}$ in $O(\alpha_S^2)$. The error is dominated by the theoretical uncertainties. Application of recent calculations, which include the resummation of leading and next-to-leading logarithms to all orders for some

observables, confirm this result with a reduced sensitivity to renormalization scale variations. The Z^0 line shapes and τ -lepton branching ratios yield $\alpha_S(M_{Z^0}) = 0.148 \pm 0.021$ and $\alpha_S(M_{Z^0}) = 0.123^{+0.006}_{-0.007}$, respectively, in $O(\alpha_S^3)$. These measurements and their uncertainties are entirely independent of each other and from event shape and jet observables; the good agreement of the resulting α_S values thus constitutes an important consistency check of the reliability of perturbative QCD.

Heavy Flavour Physics

OPAL has determined the width for $Z^0 \rightarrow b\bar{b}$ from both electron and muon semileptonic decays:

$$\frac{\Gamma_{b\bar{b}}}{\Gamma_{had}} B(b \rightarrow eX) = 0.0238 \pm 0.0008 \pm 0.0020$$

$$\frac{\Gamma_{b\bar{b}}}{\Gamma_{had}} B(b \rightarrow \mu X) = 0.0226 \pm 0.0007 \pm 0.0013.$$

OPAL has also made a measurement of the average of the B_d^0 and the B_s^0 mixing parameters:

$$\chi = 0.145^{+0.041}_{-0.035} \pm 0.018.$$

The average B hadron lifetime was measured to be $1.37 \pm 0.07 \pm 0.06$ ps from the lepton impact parameter distribution. A measurement of the τ lepton lifetime from an average of one-prong decay impact parameter and decay length of three-prong decays of 0.308 ± 0.013 ps has been reported. More precise lifetime measurements using the silicon microvertex detector should be reported shortly.

Evidence for the production of b -flavoured baryons in Z^0 hadronic decays has been found in the form of an excess of $\Lambda 1^-$, $\bar{\Lambda} 1^+$ events over $\Lambda 1^+$, $\bar{\Lambda} 1^-$ events (Ref. 2). $\Lambda 1^-$ and $\bar{\Lambda} 1^+$ events are expected to arise from semileptonic decays of b baryons. The $p\pi^-$ mass distributions for right-sign and wrong-sign lepton correlations are shown in Fig.5.

Xin Chou Lou of Indiana University was the principal author of this paper, and Thierry Mouthuy also worked on the analysis.

The Search for New Particles

OPAL has searched for the currently undiscovered particles predicted by the Standard Model, and for most particles predicted by theories beyond the Standard Model. Searches have been performed to look for:

- Stable heavy neutrinos
- Top and heavy b -type quarks
- Heavy leptons
- Excited leptons
- Neutralinos
- Technipions
- Charged Higgs
- Other SUSY particles

No positive signals were observed. Mass limits are typically at the kinematic limit of the center-of-mass energy:

The Standard Model Higgs has been excluded from 0 to 51.0 GeV, at the 95% C.L. Limits have also been placed on the masses of minimal SUSY Higgses, h^0 and A^0 .

3. Indiana University Participation in OPAL

Indiana University Personnel

Members of the Indiana University group at OPAL are:

Faculty: Gail Hanson, Harold Ogren

Research Physicists: Ronen Mir, David Rust

Postdocs: Xin Chou Lou, replacement for Thierry Mouthuy

Graduate students: Michael Settles, Eduardo Silva, plus one more

Software engineer: Thom Sulanke

The Indiana University Group officially joined OPAL in June, 1990. Indiana University is listed on OPAL papers beginning with those submitted in January, 1991.

Indiana University normally has four physicists in residence at CERN. Currently they are Gail Hanson, Xin Chou Lou, Ronen Mir, and Eduardo Silva. We are also searching for a postdoc to replace Thierry Mouthuy, who left the group for a permanent position at the Centre de Physique des Particules de Marseille; the new postdoc will be resident at CERN. During the summer of 1992, Michael Settles will return to CERN and Gail Hanson and Eduardo Silva will return to Indiana University. Harold Ogren, David Rust, and Gail Hanson will continue to spend several periods at CERN during the academic year with longer stays in the summer.

We are contributing to the OPAL experiment in the following areas:

- Offline Analysis Computing Upgrade
- Silicon Microvertex Detector
- Data Analysis
- Manpower for Running Shifts
- OPAL Common Maintenance and Operation Funds

Offline Analysis Computing Upgrade

Since CERN provides only enough computing capability to analyze about 10 percent of the data at the LEP design luminosity, the LEP experiments have had to

provide their own computing. Under the leadership of physicists from Indiana University, the OPAL Collaboration has implemented an offline analysis computing upgrade based on RISC processors and access to the data via a high-speed (1 Gbit/s) UltraNet network. RISC computers from various vendors can be used, as long as they have a UNIX operating system and an UltraNet interface. We formed a joint project with the CERN CN (Computing and Networking) Division to carry out the *SHIFT* pilot project (*SHIFT* stands for Scalable Heterogeneous Integrated FaciliTy). The pilot project consisted of about 100 MIPS of CPU server, disk servers, about 30 Gbytes of SCSI disks, a Cisco IP router, and the UltraNet backplane and network. In late 1990 Indiana University purchased a Silicon Graphics 4D 340S for the CPU server and 20 Gbytes of Wren VII SCSI disks. CN purchased the UltraNet hardware and the disk server(s). The equipment was in place by late December, 1990. Indiana University physicists set up the OPAL analysis codes on *SHIFT* and wrote procedures (in UNIX) to take care of the different environments and ease the submission of jobs by the OPAL physicists. They also wrote documentation and assist other OPAL physicists to run their analysis jobs on *SHIFT*. Thierry Mouthuy played a crucial role in setting up *SHIFT* and making it run smoothly.

SHIFT is now the primary facility for OPAL data analysis and has been expanded, both for OPAL and for other groups. In late 1991, Indiana University purchased two more Silicon Graphics 340S computers, so that *SHIFT* now has over 400 MIPS of CPU. The current *SHIFT* configuration is shown in Fig.6. Before the 1992 data were added, there were about 100 Gbytes of SCSI disk accessible on *SHIFT*. For the 1992 data, 80 Gbytes will be added (we will have to be more economical in our storage of data). *SHIFT* is a forefront computing system for the balanced I/O and CPU power needed for a large number of physicists to analyze 100's of Gbytes of data, and similar systems are now being implemented at several high energy physics laboratories in the U.S. and Europe.

Silicon Microvertex Detector

The goal of the Silicon Microvertex Detector Project is to install a high resolution, two-coordinate readout, microvertex detector, close to the interaction point in OPAL. The project is proceeding in two phases: Phase I is a one-coordinate (r - ϕ) readout detector; Phase II is a two-coordinate (r - ϕ and r - z) readout, microvertex detector; r - ϕ is

the position in the x - y plane perpendicular to the beam, at the interaction point; r - z is the position in a plane parallel to the beam.

Phase I. In March 1991 OPAL installed a two-layer Silicon MicroVertex Detector (SMVD) with a new beryllium beam-pipe of 5.5 cm radius. This detector helps in the tagging of secondary vertices, and is used in τ and B physics measurements. The SMVD consists of 14 ladders in the outer layer and 11 ladders in the inner layer, surrounding the beam pipe. Each ladder is constructed out of 3 daisy-chained silicon microstrip detectors. The detectors have a surface area of 60×33 mm, and are 300 μm thick. Each detector has 600 readout strips, parallel to the beam pipe, enabling a position measurement in the r - ϕ plane with an accuracy of ~ 10 μm . The detectors are coupled to readout electronics which include multiplexing chip and local sequencer chip, on a ceramic logic board.

These detectors are made from n -type silicon wafer sandwiched between p + strips on one side and a n + region on the other side. Around the p + strips there is a guard ring of the same p + type material as the strips to prevent charge flowing to the edges of the wafer. Under a reversed bias voltage a depleted region is developed across the bulk. The passage of a minimum ionizing particle creates electron-hole pairs. The generated charge is collected by the p + strips. The p + strips are connected to the voltage bias line through high resistance (>10 M Ω) region, to suppress the noise. The voltage supplied to this region determines its resistance. To prevent the leakage current from being fed into the readout system, the p + strips are AC coupled to aluminized readout strips. The aluminum strips are bonded to low noise - low power amplifiers.

The SMVD has been recording data faultlessly since June 1991. The signal/noise ratio obtained (in the experiment) exceeds 22/1. We currently have approximately 250,000 hadronic Z^0 decays recorded with the SMVD. This data is used to obtain the lifetime of the τ lepton, and average B lifetimes. Indiana University contributed to the purchasing of the silicon detectors in use. Lou participated in the alignment of the SMVD inside the OPAL detector.

During the 1992 run we will continue to record data with the current SMVD. We will use the data to make semi-exclusive and exclusive measurements of B decays, and expect eventually to measure $B_s^0 \bar{B}_s^0$ mixing directly.

Phase II. Based on the experience gained from Phase I, the goal of Phase II is to design and construct a detector enabling both $r-\phi$ and $r-z$ measurements with a spatial resolution of $\sim 10\ \mu\text{m}$. This would significantly improve OPAL's z position resolution.

The geometrical layout and mechanics of Phase II are identical to Phase I. The silicon detectors are different, as is the readout electronics. Two types of silicon detectors are currently being investigated:

(1) Double-sided detector: silicon detectors with $r-\phi$ $p+$ strips on one side, (the ϕ side), and $r-z$ $n+$ strips interleaved with $p+$ implants on the other side (the z side). The high resistance regions connecting the $p+$ and $n+$ strips to the voltage bias lines are obtained by implants of polysilicon resistors. Landau correlations between both sides can be studied. These detectors are manufactured by the Canberra Company.

(2) Back-to-back detector: two single-sided detectors, as in the Phase I design, with strips in orthogonal directions. A detector with $r-\phi$ strips is glued to a detector with $r-z$ strips. These are manufactured by the Micron Company.

Indiana University is one of the major institutions involved in Phase II work since April of 1991. We have three people working on the project (Mir, Rust and Silva), and are contributing both in equipment and in silicon costs.

Studies of Prototype Detectors for Phase II. Indiana University is in charge of most prototype detector studies for Phase II. These include visual inspection of the detectors, leakage current measurements, resistance and diode measurements, and radiation hardness tests. Mir and Silva are currently working on these tests.

Visual Inspection: Using the Indiana analysis station (see Equipment below) we visually scan and record all detectors arriving at CERN. The faults observed are correlated to noisy channels during the readout tests.

Leakage Current: Using the analysis station and a set of custom-built jigs, we apply voltage to each detector, bringing it to the depletion zone, and monitor its leakage currents. These measurements are carried over long time periods (up to 500 hours) to give us confidence in the long term stability of our detectors. Those detectors whose

leakage current increases significantly are cured at a temperature of 200° C, a procedure which is intended to lower and stabilize the currents.

Resistor and Diode Measurements: We get from the manufacturers test structures which include resistors and diodes from each silicon wafer used to make each detector. These test structures are supposed to have identical properties to the actual detectors. Using the analysis station, we monitor the resistance values and diode currents in these test structures, thereby getting a good idea of the detector's properties. We further probe some of the polysilicon resistor structures on the double-sided Canberra detectors to check uniformity of resistance values across the 1200 resistors implanted on each detector.

Radiation hardness tests: We subject a sample of the detectors to a radiation dose of up to 200 krad, and monitor their physical properties as a function of the absorbed radiation. We place our samples in a high radiation (~ 1 krad/hour) β source (Sr^{90}). We measure the leakage current while the sample is in the source, keeping it at operational voltage. We further measure all physical properties of the detector after the radiation exposure. These tests are crucial in simulating the radiation conditions at LEP over the experiment's lifetime.

Equipment for Phase II. In April 1991, when IU joined the laboratory work on SMVD Phase II, the equipment for analyzing silicon detectors consisted of a single low-magnification microscope. There was no equipment for complete analyses of detectors, either visually or by structure probing.

We embarked on a thorough survey of the various techniques used in silicon MVD research. We visited three other silicon development laboratories at CERN, and met with representatives of silicon analyzing equipment manufacturers.

As a result of these studies, a state of the art analysis station was ordered from the Alessi company, together with a high-magnification microscope, as well as video cameras and monitors. The analysis station is Alessi model REL-3200A with the following properties:

- Lever-actuated platen lift, user adjustable; room for 12 micropositioners
- 4" stainless steel vacuum chuck planarized to $\pm 10 \mu\text{m}$, with 90° theta motion

- 4" × 4" precision stage, with 1 μm resolution
- 1" linear vacuum chuck z motion
- Motorized 4" × 4" microscope transport
- Vibration isolation feet
- Instrumentation interface via 14 color coded plugs

On this station is mounted a Bausch & Lomb Microzoom microscope with a magnification of 22.5 to 500. To the microscope we have attached a CCTV (charge couple color video camera) and high resolution color monitor. To probe the various silicon structures we have 8 high resolution micropositioners with various probe tips of 0.6 - 2.4 μm radius. The cost of the analysis test station, the microscope, the CCTV and monitor, and the 8 micropositioners was \$40K.

The analysis station is used for most of the evaluation tests described above, as well as for tests of other crucial components such as a z readout structure and a glass pitch adapter. Its contribution to the fast and accurate evaluation of the various components in the project is substantial. The analysis station is also been heavily utilized by the Forward Calorimeter Silicon Tungsten Project for intensive scanning and testing of their Amplex readout chip.

Data Analysis Activities

The Indiana group have been leaders in semi-exclusive and exclusive B physics analyses. Some of this work was described in Section 2. Xin Chou Lou was the principal author on the paper on b -flavoured baryon production (Ref. 2). Thierry Mouthuy also contributed to this analysis.

The Indiana physicists, plus others in OPAL, are now concentrating on evidence for the B_s . Gail Hanson is coordinating the "exclusive B-decay working group," which is preparing new results for the summer conferences. Xin Chou Lou is working on D_s -lepton correlations, which are evidence for the decay $B_s^0 \rightarrow D_s^+ l^- \bar{\nu} X$. The D_s is reconstructed from the decays $D_s^+ \rightarrow \phi \pi^+$ or $\bar{K}^{*0} K^+$. He has had evidence for this signal for about a year, but it was not sufficiently statistically significant until recently. He has also had to work on understanding the backgrounds. This analysis uses all of the 1990

and 1991 data and does not require the silicon microvertex detector. Ronen Mir is working on reconstruction of exclusive B_s decays into $D_s (n \pi)$. The D_s is reconstructed as in Lou's analysis. Mir may also have the beginnings of a signal, and is studying the optimization of cuts and backgrounds through Monte Carlo work. None of this work is public at the time of this writing. ALEPH and DELPHI have reported D_s -lepton correlation signals, but their results are not more significant than ours. We prefer to make a more careful study before making public announcements.

Lou is also working with an OPAL student on charmed baryon Λ_c^+ -lepton correlation signals and has had some success. Λ_c^+ -lepton correlations are signals for semileptonic decay of the b -flavoured baryon Λ_b (quark composition bud). The Λ_c^+ -lepton correlation signals confirm our published result on b -flavoured baryons based on Λ -lepton correlations. Properties of the semileptonic decay of the Λ_b are under study. This analysis may also be reported at summer conferences.

Hanson and Eduardo Silva are beginning a study of charmed meson production making use of the silicon microvertex detector. Studies of $B_{u,d}$ decays to charm plus lepton are needed to complete the picture.

The OPAL Collaboration assigns an editorial board to a physics analysis project that has obtained results to be developed for publication. Together with the principal authors, who carry out the analysis, the editorial board is responsible the physics results. Two Indiana University physicists have served on editorial boards. OPAL has four weekly plenary meetings a year. OPAL physicists also have the opportunity to give reports to the entire collaboration every Thursday ("OPAL Thursday talks"). Contributions to OPAL from Indiana physicists are listed at the end of this section.

CONTRIBUTIONS FROM INDIANA UNIVERSITY PHYSICISTS

Gail Hanson, Xin Chou Lou, Ronen Mir, Thierry Mouthuy

OPAL Internal Notes

"OPAL USERS' GUIDE FOR THE *SHIFT* PROJECT," G. Hanson *et al.*

Thierry Mouthuy

Invited Talks

"*SHIFT*: OPAL'S COMPUTING ENVIRONMENT FOR PHYSICS ANALYSIS," Talk at DESY, December 1991.

"*SHIFT* COMPUTER FORUM," CN Division presentation with Bernd Panzer, September 1991.

Xin Chou Lou

Publications

"EVIDENCE FOR *b*-FLAVOURED BARYON PRODUCTION IN Z^0 DECAYS AT LEP," OPAL Collaboration, P. D. Acton *et al.*, CERN-PPE/92-34, accepted by Phys. Lett. B., Principal author.

Invited Talks

"THE HUNT FOR *b* BARYONS -- 10 YEARS AFTER THE START," Physics Department Colloquium at Ohio State University, March 30, 1992.

"RESULTS ON *b* BARYONS FROM OPAL," Discussion meeting on the Λ_b baryon, attended by representatives from ALEPH, CDF, INFN, OPAL and UA1, Istituto Nazionale di Fisica Nucleare, Pisa, Italy, March 16, 1992.

"EVIDENCE FOR *b*-FLAVOURED BARYON PRODUCTION IN Z^0 DECAYS AT LEP," Invited talk at "Results and Perspectives in Particle Physics," La Thuile, Aosta Valley, Italy, March 8-14, 1992.

OPAL Plenary Talks

"*b*-FLAVOURED BARYONS AND THE DECAY $B^0 \rightarrow D^{*-} 1^+ \bar{\nu}$ -- STATUS REPORT," September 19, 1991.

" D_s^+ PRODUCTION AND A SEARCH FOR b -FLAVOURED BARYONS,"
June 27, 1991.

OPAL Thursday Talks

"STATUS OF B_s^0 SEARCH AT OPAL," April 16, 1992.

"NEWS ON B PHYSICS FROM LA THUILE," March 19, 1992.

" b -BARYON VIA BARYON-LEPTON CORRELATION," November 1, 1991.

OPAL Internal Notes

"STUDY OF $D_s^+ l^-$ CORRELATION IN Z^0 DECAYS," Physics Note, in preparation.

OPAL Editorial Boards

"STRANGE BARYON PRODUCTION IN Z^0 DECAYS AT LEP," Paper in preparation.

"A STUDY OF K_s^0 PRODUCTION IN Z^0 DECAYS," OPAL Collaboration, CERN-PPE/91-86, Phys. Lett. **264B**, 467 (1991).

Ronen Mir

Invited Talks

" Z^0 , THE MODEL AND BEAUTY AT LEP," Physics Department Colloquium, Indiana University, November 13, 1991.

" B PHYSICS WITH THE OPAL DETECTOR," Seminar at University of Montreal, November 7, 1991.

"RESULTS FROM THE OPAL DETECTOR," Seminar at University College, London, October 28, 1991.

" B PHYSICS WITH THE OPAL DETECTOR," Seminar at the Weizmann Institute and Technion, Israel, June 1991.

"THIN MULTIWIRE CHAMBERS FOR THE HADRON CALORIMETER," Talk at the Tau Charm Factory Meeting, Seville, Spain, May 1991.

"ONLINE/OFFLINE COMPUTING FACILITIES," Talk at the Tau Charm Factory Meeting, Seville, Spain, May 1991.

OPAL Plenary Talks

"THE *SHIFT* PROJECT FOR PHYSICS ANALYSES," March 1991.

OPAL Editorial Boards

"SEARCH FOR MASSIVE UNSTABLE PHOTINOS THAT VIOLATE R PARITY," Paper in preparation.

"DECAY MODE INDEPENDENT SEARCH FOR A LIGHT HIGGS BOSON AND NEW SCALARS," OPAL Collaboration, CERN-PPE/91-116, Phys. Lett. **268B**, 122 (1991).

"OBSERVATION OF J/Ψ PRODUCTION IN MULTIHADRONIC Z^0 DECAYS," OPAL Collaboration, CERN-PPE/91-92, Phys. Lett. **266B**, 485 (1991).

OPAL Contribution

OPAL coordinator for the visit of Dr. James F. Decker, Deputy Director, Office of Energy Research, DOE.

Gail Hanson

Invited Talks

"RECENT RESULTS ON PHYSICS AT THE Z^0 RESONANCE AT LEP," Plenary talk at the Spring Meeting of the Ohio Section of the American Physical Society, Cincinnati, Ohio, May 9, 1992.

"RECENT RESULTS FROM LEP," Physics Department Colloquium at University of Illinois, Urbana-Champaign, February 6, 1992.

" e^+e^- PHYSICS AT THE Z^0 RESONANCE AT CERN," Oberlin College Colloquium, October 18, 1991.

"RECENT RESULTS FROM LEP," Indiana University High Energy Physics Seminar, October 1, 1991.

"RECENT RESULTS FROM LEP," CEBAF Colloquium, September 18, 1991.

OPAL Contribution

Coordinator of Exclusive B-decay Working Group, Spring 1992

OPAL PUBLICATIONS

1. A MEASUREMENT OF ELECTRON PRODUCTION IN HADRONIC Z^0 DECAYS AND A DETERMINATION OF $\Gamma(Z^0 \rightarrow b\bar{b})$, OPAL Collaboration, CERN-PPE/92-38, submitted to Z. für Physik C.
2. EVIDENCE FOR b -FLAVOURED BARYON PRODUCTION IN Z^0 DECAYS AT LEP, OPAL Collaboration, CERN-PPE/92-34, submitted to Phys. Lett. B.
3. A GLOBAL DETERMINATION OF $\alpha_s(M_{Z^0})$ AT LEP, OPAL Collaboration, CERN-PPE/92-18, submitted to Z. für Physik C.
4. TEST OF CP-INVARIANCE IN $e^+e^- \rightarrow Z^0 \rightarrow \tau^+\tau^-$ AND A LIMIT ON THE WEAK DIPOLE MOMENT OF THE τ LEPTON, OPAL Collaboration, CERN-PPE/92-14, submitted to Phys. Lett. B.
5. ELECTROWEAK PARAMETERS OF THE Z^0 RESONANCE AND THE STANDARD MODEL, The LEP Collaborations: ALEPH, DELPHI, L3 AND OPAL, CERN-PPE/91-232, submitted to Phys. Lett. B.
6. SEARCH FOR FREE GLUONS IN HADRONIC Z^0 DECAYS, OPAL Collaboration, CERN-PPE/91-230, submitted to Phys. Lett. B.
7. AN IMPROVED MEASUREMENT OF $\alpha_s(M_{Z^0})$ USING ENERGY CORRELATIONS WITH THE OPAL DETECTOR AT LEP, OPAL Collaboration, CERN-PPE/91-214, Phys. Lett. **276B**, 547 (1991).
8. MEASUREMENT OF $B^0\bar{B}^0$ MIXING IN HADRONIC Z^0 DECAYS, OPAL Collaboration, CERN-PPE/91-212, submitted to Phys. Lett. B.
9. MEASUREMENT OF THE AVERAGE B HADRON LIFETIME IN Z^0 DECAYS, OPAL Collaboration, CERN-PPE/91-201, submitted to Phys. Lett. B.
10. PROPERTIES OF MULTIHADRONIC EVENTS WITH A FINAL STATE PHOTON AT $\sqrt{s} = M_{Z^0}$, OPAL Collaboration, CERN-PPE/91-189, submitted to Z. für Physik C.
11. A STUDY OF CHARGED PARTICLE MULTIPLICITIES IN HADRONIC DECAYS OF THE Z^0 , OPAL Collaboration, CERN-PPE/91-176, submitted to Z. für Physik C.
12. MEASUREMENT OF THE τ LEPTON LIFETIME, OPAL Collaboration, CERN-PPE/91-164, Phys. Lett. **273B**, 355 (1991).
13. A MEASUREMENT OF PHOTON RADIATION IN LEPTON PAIR EVENTS FROM Z^0 DECAYS, OPAL Collaboration, CERN-PPE/91-155, Phys. Lett. **273B**, 338 (1991).

14. DECAY MODE INDEPENDENT SEARCH FOR A LIGHT HIGGS BOSON AND NEW SCALARS, OPAL Collaboration, CERN-PPE/91-116, Phys. Lett. **268B**, 122 (1991).
15. A STUDY OF BOSE-EINSTEIN CORRELATIONS IN e^+e^- ANNIHILATIONS AT LEP, OPAL Collaboration, CERN-PPE/91-110, Phys. Lett. **267B**, 143 (1991).
16. MEASUREMENT OF BRANCHING RATIOS AND τ POLARIZATION FROM $\tau \rightarrow e \nu \bar{\nu}$, $\tau \rightarrow \mu \nu \bar{\nu}$, and $\tau \rightarrow \pi (K) \nu$ DECAYS AT LEP, OPAL Collaboration, CERN-PPE/91-103, Phys. Lett. **266B**, 201 (1991).
17. MEASUREMENT OF THREE-JET DISTRIBUTIONS SENSITIVE TO THE GLUON SPIN IN e^+e^- ANNIHILATIONS AT $\sqrt{s} = 91$ GEV, OPAL Collaboration, CERN-PPE/91-97, Z. für Physik **52C**, 543 (1991).
18. OBSERVATION OF J/ψ PRODUCTION IN MULTIHADRONIC Z^0 DECAYS, OPAL Collaboration, CERN-PPE/91-92, Phys. Lett. **266B**, 485 (1991).
19. A DIRECT OBSERVATION OF QUARK-GLUON JET DIFFERENCES AT LEP, OPAL Collaboration, CERN-PPE/91-91, Phys. Lett. **265B**, 462 (1991).
20. A STUDY OF K_s^0 PRODUCTION IN Z^0 DECAYS, OPAL Collaboration, CERN-PPE/91-86, Phys. Lett. **264B**, 467 (1991).
21. A MEASUREMENT OF THE ELECTROWEAK COUPLINGS OF UP AND DOWN TYPE QUARKS USING FINAL STATE PHOTONS IN HADRONIC Z^0 DECAYS, OPAL Collaboration, CERN-PPE/91-81, Phys. Lett. **264B**, 219 (1991).
22. ELECTROWEAK COUPLINGS OF CHARGED LEPTONS, OPAL Collaboration, CERN-PPE/91-67, Z. für Physik **52C**, 175 (1991).
23. A STUDY OF $D^{*\pm}$ PRODUCTION IN Z^0 DECAYS, OPAL Collaboration, CERN-PPE/91-63, Phys. Lett. **262B**, 341 (1991).
24. A SEARCH FOR SCALAR LEPTOQUARKS IN Z^0 DECAYS, OPAL Collaboration, CERN-PPE/91-61, Phys. Lett. **263B**, 123 (1991).
25. A STUDY OF HEAVY FLAVOUR PRODUCTION USING MUONS IN HADRONIC Z^0 DECAYS, OPAL Collaboration, CERN-PPE/91-48, Phys. Lett. **263B**, 311 (1991).
26. INTERMITTENCY IN HADRONIC DECAYS OF THE Z^0 , OPAL Collaboration, CERN-PPE/91-37, Phys. Lett. **262B**, 351 (1991).
27. A MODEL INDEPENDENT OBSERVATION OF THE STRING EFFECT USING QUARK TAGGING AT LEP, OPAL Collaboration, CERN-PPE/91-31, Phys. Lett. **261B**, 334 (1991). (First paper with Indiana University names.)

28. MEASUREMENT OF THE CROSS SECTIONS OF THE REACTIONS $e^+e^- \rightarrow \gamma\gamma$ AND $e^+e^- \rightarrow \gamma\gamma\gamma$ AT LEP, OPAL Collaboration, CERN-PPE/90-189, Phys. Lett. **257B**, 531 (1991).
29. A DIRECT MEASUREMENT OF THE Z^0 INVISIBLE WIDTH BY SINGLE PHOTON COUNTING, OPAL Collaboration, CERN-PPE/90-187, Z. für Physik **50C**, 373 (1991).
30. SEARCH FOR THE MINIMAL STANDARD MODEL HIGGS BOSON IN e^+e^- COLLISIONS AT LEP, OPAL Collaboration, CERN-PPE/90-150, Phys. Lett. **253B**, 511 (1991).
31. A SEARCH FOR LEPTON FLAVOUR VIOLATION IN Z^0 DECAYS, OPAL Collaboration, CERN-PPE/90-148, Phys. Lett. **254B**, 293 (1991).
32. A STUDY OF THE RECOMBINATION SCHEME DEPENDENCE OF JET PRODUCTION RATES AND OF $\alpha_S(M_{Z^0})$ IN HADRONIC Z^0 DECAYS, OPAL Collaboration, CERN-PPE/90-143, erratum to CERN-PPE/90-143, Z. für Physik **49C**, 375 (1991).
33. SEARCH FOR PAIR PRODUCED STABLE SINGLY-CHARGED HEAVY PARTICLES IN Z^0 DECAYS, OPAL Collaboration, CERN-PPE/90-132, Phys. Lett. **252B**, 290 (1990).
34. A MEASUREMENT OF ENERGY CORRELATIONS AND A DETERMINATION OF $\alpha_S(M_{Z^0}^2)$ IN e^+e^- ANNIHILATIONS AT $\sqrt{s} = 91$ GEV, OPAL Collaboration, CERN-PPE/90-121, Phys. Lett. **252B**, 159 (1990).
35. LIMITS ON A LIGHT HIGGS BOSON IN e^+e^- COLLISIONS AT LEP, OPAL Collaboration, CERN-PPE/90-116, Phys. Lett. **251B**, 211 (1990).
36. THE OPAL DETECTOR AT LEP, OPAL Collaboration, CERN-PPE/90-114, Nucl. Instr. and Meth. **A305**, 275 (1991).
37. SEARCHES FOR NEUTRAL HIGGS BOSONS IN e^+e^- COLLISIONS AT LEP, OPAL Collaboration, CERN-EP/90-100, Z. für Physik **49C**, 1 (1990).
38. A STUDY OF ANGULAR CORRELATIONS IN 4-JET FINAL STATES OF HADRONIC Z^0 DECAYS, OPAL Collaboration, CERN-EP/90-97, Z. für Physik **49C**, 49 (1990).
39. A DIRECT SEARCH FOR NEUTRALINO PRODUCTION AT LEP, OPAL Collaboration, CERN-EP/90-95, Phys. Lett. **248B**, 211 (1990).
40. A STUDY OF COHERENCE OF SOFT GLUONS IN HADRON JETS, OPAL Collaboration, CERN-EP/90-94, Phys. Lett. **247B**, 617 (1990).
41. ANALYSIS OF Z^0 COUPLINGS TO CHARGED LEPTONS, OPAL Collaboration, CERN-EP/90-81, Phys. Lett. **247B**, 458 (1990).

42. LIMITS ON NEUTRAL HEAVY LEPTON PRODUCTION FROM Z^0 DECAY, OPAL Collaboration, CERN-EP/90-72, Phys. Lett. **247B**, 448 (1990).
43. EVIDENCE FOR FINAL STATE PHOTONS IN MULTIHADRONIC DECAYS OF THE Z^0 , OPAL Collaboration, CERN-EP/90-55, Phys. Lett. **246B**, 285 (1990).
44. SEARCH FOR EXCITED LEPTONS AT LEP, OPAL Collaboration, CERN-EP/90-49, Phys. Lett. **244B**, 135 (1990).
45. A MEASUREMENT OF GLOBAL EVENT SHAPE DISTRIBUTIONS IN THE HADRONIC DECAYS OF THE Z^0 , OPAL Collaboration, CERN-EP/90-48, Z. für Physik **47C**, 505 (1990).
46. A SEARCH FOR TECHNIPIONS AND CHARGED HIGGS BOSONS AT LEP, OPAL Collaboration, CERN-EP/90-38, Phys. Lett. **242B**, 299 (1990).
47. A STUDY OF THE REACTION $e^+e^- \rightarrow \gamma\gamma$ AT LEP, OPAL Collaboration, CERN-EP/90-29, Phys. Lett. **241B**, 133 (1990).
48. A COMBINED ANALYSIS OF THE HADRONIC AND LEPTONIC DECAYS OF THE Z^0 , OPAL Collaboration, CERN-EP/90-27, Phys. Lett. **240B**, 497 (1990).
49. A DIRECT SEARCH FOR NEW CHARGED HEAVY LEPTONS AT LEP, OPAL Collaboration, CERN-EP/90-09, Phys. Lett. **240B**, 250 (1990).
50. A SEARCH FOR ACOPLANAR PAIRS OF LEPTONS OR JETS IN Z^0 DECAYS: MASS LIMITS ON SUPERSYMMETRIC PARTICLES, OPAL Collaboration, CERN-EP/89-176, Phys. Lett. **240B**, 261 (1990).
51. A SEARCH FOR NEW CHARGED HEAVY LEPTONS WITH THE OPAL DETECTOR AT LEP, OPAL Collaboration, CERN-EP/89-175.
52. MASS LIMITS FOR A STANDARD MODEL HIGGS BOSON IN e^+e^- COLLISIONS AT LEP, OPAL Collaboration, CERN-EP/89-174, Phys. Lett. **236B**, 224 (1990).
53. A SEARCH FOR THE TOP AND b' QUARKS IN HADRONIC Z^0 DECAYS, OPAL Collaboration, CERN-EP/89-154, Phys. Lett. **236B**, 364 (1990).
54. A STUDY OF JET PRODUCTION RATES AND A TEST OF QCD ON THE Z^0 RESONANCE, OPAL Collaboration, CERN-EP/89-153, Phys. Lett. **235B**, 389 (1990).
55. MEASUREMENT OF THE DECAY OF THE Z^0 INTO LEPTON PAIRS, OPAL Collaboration, CERN-EP/89-147, Phys. Lett. **235B**, 379 (1990).
56. MEASUREMENT OF THE Z^0 MASS AND WIDTH WITH THE OPAL DETECTOR AT LEP, OPAL Collaboration, CERN-EP/89-133, Phys. Lett. **231B**, 530 (1989).

Fig. 1. Schematic view of the OPAL Detector.

Fig. 2. Schematic view of the OPAL silicon microvertex detector.

Fig.3. Impact parameter distribution for $Z^0 \rightarrow \mu^+\mu^-$ events before (dashed curve) and after (solid curve) the silicon microvertex detector.

Fig. 4. Compilation of final results of $\alpha_s(M_{Z0})$. The top shaded band corresponds to the weighted average of $\alpha_s(M_{Z0}) = 0.122^{+0.006}_{-0.005}$ from the measurements in $O(\alpha_s^2)$, and the bottom shaded band to $\alpha_s(M_{Z0}) = 0.125 \pm 0.006$ from the two $O(\alpha_s^3)$ results (from Ref. 3).

Fig.5. a) The $p\pi^-$ invariant mass distribution of the Λ particles for Λe^- candidates (hatched histogram) and for $\Lambda \mu^-$ candidates (open histogram). b) The $p\pi^-$ invariant mass distribution of the Λ particles for Λe^+ candidates (hatched histogram) and for $\Lambda \mu^+$ candidates (open histogram). (From Ref. 2.)

the *shift* configuration at CERN - March1992

Fig. 6. Current configuration of the *SHIFT* offline analysis facility.

Brookhaven Experiment 852

Looking for Mesons with Unusual Quantum Numbers

Technical Progress Report for the DoE 1991–1992

*Indiana University
High Energy Physics Group*

Ben Brabson, Ray Crittenden, Alex Dzierba, Jeff Gunter, Rob Lindenbusch,
Eric Scott, Paul Smith, Thom Sulanke and Scott Teige
E852 IU Group

Introduction

E852 is a search for mesons with unusual quantum numbers. This experiment, which will use the Multiparticle Spectrometer (MPS) at Brookhaven National Lab (BNL), will examine current issues in light-quark spectroscopy. Recent experimental results from other laboratories have revealed possible candidates for non- $q\bar{q}$ mesons. Furthermore we will bring new technology to bear on the experimental front to collect high statistics on final states expected to be rich in glueballs and exotics. The physics will be discussed in more detail below. It turns out that BNL is the ideal lab for studying mesons in the light-quark sector (1 to 2 GeV). Doing these experiments at higher energies means that cross-sections for specific exclusive processes are diminished because of the p_{LAB}^{-2} fall-off with incident momentum. At lower energies the desired final states are not produced with sufficient acceptance. This experiment calls for major upgrades to the MPS including additional particle tracking, a CsI and lead/scintillator soft photon veto, a segmented Cerenkov counter, a 3000-element lead glass detector (LGD) and a new data acquisition system. The Indiana group is in charge of the LGD and its associated read-out and trigger electronics.

The Collaboration

In addition to the Indiana group, the E852 collaboration consists of physicists from:

- Brookhaven National Lab (BNL)
- Institute of High Energy Physics (IHEP) in Serpukhov, Russia
- University of Louisville (UL)
- Moscow State University (MSU) in Russia
- University of Notre Dame (UND)
- Southeastern Massachusetts University (SMU)

The Co-Spokesman are Suh Urk Chung (BNL) and Alex R. Dzierba (IU)

Timetable

This experiment will take place starting in 1993. The experiment was originally proposed in early 1989 when it received Stage I approval. After a technical review by a committee appointed by the BNL lab management, the proposal was re-written and re-submitted in late 1989¹ and received Conditional Approval. The experiment received Final Approval in May, 1990. A second technical review took place in April, 1991. At that time we also successfully tested a 25-element prototype LGD (P1) in the A2 test beam at BNL. The P1 tests were completed in June, 1991. Since that time we have been preparing a 324-element (18 x 18 stack) prototype (P2) which has been shipped to BNL for tests in a 15 GeV pion beam in the A3 beamline. These tests will take place in May and June of 1992. This report describes the activities during the second half of 1991 and the first half of 1992.

¹ AGS Proposal P852, Oct. 1989.

Physics of E852

Quark Model and Mesons

The naive quark model has been remarkably, indeed mysteriously, successful in describing the bulk of the observed mesons. For example, if mesons are made up of $q\bar{q}$ pairs then we should not expect to find mesons with $|Q| > 1$ or $|S| > 1$, where Q and S are charge and strangeness respectively, and indeed this is the case. Furthermore, for a $q\bar{q}$ system, a fermion-antifermion system, the same quantum number restrictions as for positronium apply, namely:

$$\vec{J} = \vec{L} + \vec{S}$$

$$P = (-1)^{L+1}$$

$$C = (-1)^{L+S}$$

where S is the total quark spin (0 or 1), L is the relative orbital angular momentum, and J, P and C are the spin, parity and C-parity of the composite system. This implies that certain J^{PC} combinations are not allowed, e. g.:

$0^{+-}, 0^{-+}, 1^{-+}, \dots$ These combinations are called exotic and would provide *prima facie* evidence for a non- $q\bar{q}$ state. With one exception, no states have been seen with exotic quantum numbers. The success of the naive quark model must be dealt with in the context of quantum chromodynamics (QCD) which predicts a rich spectrum of mesons, including, but not restricted to, $q\bar{q}$ states. These are shown schematically in Fig 1. We expect $q\bar{q}$ mesons but, because of the non-Abelian character of QCD we also expect bound states of gluons (glueballs). Still other states with valence gluons (hybrids) and four-quark states ($q\bar{q}q\bar{q}$) are predicted. For the non- $q\bar{q}$ combinations the J^{PC} restrictions imposed by $q\bar{q}$ do not apply.

Fig 1: QCD Mesons

Given the success of QCD, in the perturbative regime, we must face the theoretical and experimental challenge facing us with the apparent success of the naive quark model namely: non-perturbative QCD predicts non- $q\bar{q}$ mesons for which no iron-clad experimental evidence exists. There are, however, mesons which appear to be extraneous (which would overfill existing $q\bar{q}$ nonets) or which have branching ratios peculiar for a $q\bar{q}$ state. Experiments are needed to clear up this untidiness, for if glueballs and hybrids do not exist, then we need to understand why. If experiment shows that these states do exist then their spectrum, production, and decay modes should be predicted by QCD. This challenge must be met in the non-perturbative regime where currently we have models (e.g. potential models) which can make predictions but have no theoretical underpinnings or solid theory (lattice gauge) with essentially no predictive powers. As physicists, theoretical and experimental, we cannot ignore the problem. It needs work. We do know one thing: we can expect little progress on the theory front without information from experiment.

Glueballs: Where to Look

Willy Sutton, was once asked why he robbed banks, to which he answered: "that's where the money is". QCD meson hunters can't be this slick. The neat and clean solution would be to find a flavorless exotic. Lacking this we must turn to less direct schemes. Glueballs are predicted to be singlets in color and flavor and therefore one should look for states for which there is no room in $q\bar{q}$ nonets. Fig 2 shows such a nonet. Two $I = 0$ members are anticipated. It turns out that for the vector and tensor nonets, these $I = 0$ states are nearly ideally mixed in their physical manifestations (e. g.: the ϕ and ω) such that one state is $s\bar{s}$ while the other is $(u\bar{u} + d\bar{d})/\sqrt{2}$. If one can identify candidate

Fig 2: The Light-Quark Nonet

states which overbook this area of the $q\bar{q}$ nonets and which have production rates and/or decay modes unexpected of $q\bar{q}$, then we may have found a non- $q\bar{q}$ state. Another place to look is in processes expected to be glue-rich. Two examples are radiative J/ψ decays (see Fig 3) or in OZI-forbidden processes (see Fig 4), a venue in which Lindenbaum¹ prefers to operate. Where not to look? Since gluons do not couple to charge, we should not expect glueballs to be produced in $\gamma\gamma$ collisions. What is clear is that a complementary set of experiments is needed. Experiments at LEAR, GAMS, J/ψ radiative decays, $\gamma\gamma$ collisions, OZI-forbidden processes, and so on must probe each others realm of unusual meson behavior.

Fig 3: J/ψ Radiative Decay

Fig 4: An OZI-Disallowed Process

A possible candidate for gluonium originated with the GAMS collaboration² working at IHEP (Serpukhov) and CERN which identified a scalar meson at 1590 MeV, the $G(1590)$ (also referred to as the $f_0(1590)$), decaying into $\eta\eta$ and $\eta\eta'$. They claim peculiar branching ratios for a $q\bar{q}$ meson:

$$G(1590) \rightarrow \pi^0\pi^0 : K\bar{K} : \eta\eta : \eta\eta' : 4\pi^0 \\ <0.3 : <1 : 1 : 3 : 0.8$$

Since the η and η' are expected to be glue-rich, the preferred decays into these states suggests a glueball interpretation³. The $G(1590)$ was recently confirmed by the Crystal Barrel experiment at LEAR⁴ looking at:

$$p\bar{p} \rightarrow \pi^0\eta\eta$$

Hybrids

Mention was made earlier of a possible exotic candidate. The GAMS group⁵, operating at Serpukhov and CERN claims to see a state with a mass of 1405 MeV decaying into $\eta\pi^0$ in the process:

$$\pi^- p \rightarrow \eta\pi^0 n \rightarrow 4\gamma n$$

at incident energies of 38 and 100 GeV. The assertion is that the $\eta\pi^0$ resonates in a P-wave which makes this a $J^{PC} = 1^{-+}$ exotic. Since $I = 1$ for such a state it cannot be a glueball so it is a candidate for a hybrid state. The state is not seen directly as a bump in a mass spectrum. Rather it manifests itself as an interference of a P-wave with the D-wave:

$$a_2(1320) \rightarrow \eta\pi^0$$

resulting in a marked asymmetry in the forward-backward population of the decay angular distribution in the $\eta\pi^0$ system. The GAMS experiment sees only photons. Since $I = 1$, $\eta\pi^-$ should also occur as decay products of this exotic state. Other decays modes of the neutral state are also anticipated. These include $\eta'\pi^0$ and $b_1(1235)\pi^0$ where the $b_1(1235)$ decays into $\omega\pi$. An experiment is needed to look at both charged particles and photons.

Charged Particles and π^0 , η , η'

We can learn a lesson from GAMS. It is profitable to study neutral systems like

$\pi^0\pi^0$, $\eta\pi^0$, $\eta'\pi^0$, $\eta\eta$, $\eta\eta'$. For such systems $J^{PC} = 0^{++}, 1^{-+}, 2^{++} \dots$. If $\eta\pi^0$ resonates in a P-wave J^{PC} is exotic and not a glueball ($I = 1$). If $\eta\eta'$ resonates in a P-wave, again J^{PC} is exotic but now a glueball candidate ($I = 0$). Seeing $\pi^0\pi^0$ or $\eta\eta$ decays requires J (and L) to be even.

However restricting the experiment to all photon decays of the η and η' precludes other decays such as:

$$\eta \rightarrow \pi^+\pi^-\pi^0 \quad \eta' \rightarrow \pi^+\pi^-\eta \quad \eta' \rightarrow \rho^0\gamma$$

We note that although the BR for $\eta \rightarrow 2\gamma$ is substantial (40 %), the BR for $\eta' \rightarrow 2\gamma$ is

meager (2 %). Besides providing more statistics these other modes provide us with an excellent check on the systematics of the experiment. Our partial wave analysis (PWA) had better give us the same answers regardless of how the η or η' decay. E852 will be able to look at both charged particles and photons. Our trigger will require a certain charged particle multiplicity (0, 1 or 2) and will make requirements on the multi-photon effective mass.

Multi-Photon Effective Mass Trigger

It is clear that decay modes involving:

π^0 , η , ω , η' are important. Our trigger (to be discussed in more detail below) will allow us to trigger on:

$$\pi^0 \rightarrow 2\gamma \quad \eta \rightarrow 2\gamma \quad \omega \rightarrow \pi^0\gamma \rightarrow 3\gamma \quad \eta' \rightarrow 2\gamma$$

with the LGD by reconstructing the photon 3-vectors in the trigger. This will give us an enriched sample for the PWA.

Radiative ϕ Decays

E852 will also be able to probe these ϕ radiative decays⁶, listed with their BR:

$$\begin{aligned} \phi \rightarrow \pi^0\gamma & (1.31 \pm 0.13) \cdot 10^{-3} \\ \phi \rightarrow \eta^0\gamma & (1.28 \pm 0.06) \cdot 10^{-2} \\ \phi \rightarrow \omega^0\gamma & < 5 \cdot 10^{-2} \\ \phi \rightarrow \eta'\gamma & < 4 \cdot 10^{-4} \\ \phi \rightarrow K\bar{K}\gamma & ? \end{aligned}$$

It is interesting to see that the decay involving the ω has a rather imprecise limit. This decay is C-violating and not expected to occur. We should be able to improve this limit by at least two orders of magnitude⁷. The decay involving the η' , although not forbidden is nevertheless not kinematically encouraged, is of interest

since it provides a way, in conjunction with the decay involving the η , to measure the $s\bar{s}$ content of these mesons. Phase space dominates the BR into η' . Indeed:

$$\frac{BR(\phi \rightarrow \eta' \gamma)}{BR(\phi \rightarrow \eta \gamma)} = \left(\frac{m_\phi^2 - m_{\eta'}^2}{m_\phi^2 - m_\eta^2} \right)^3 \left| \frac{y_{\eta'}}{y_\eta} \right|^2$$

$$= (7 \cdot 10^{-5}) \left| \frac{y_{\eta'}}{y_\eta} \right|^2$$

where the y 's measure $s\bar{s}$ the content⁸. In a 2000 hour run we expect about 400 decays into η' if the $s\bar{s}$ content of the η and η' are comparable. Finally the $K\bar{K}\gamma$ decay is of interest to ϕ factories⁹ which plan to study CP violation by using the decay:

$$\phi \rightarrow K_S K_L$$

Seeing K_S the tags the recoil as a K_L . However, the radiative process:

$$\phi \rightarrow \gamma(K_L K_L \text{ or } K_S K_S)$$

is a potential background since since the radiated photon carries only 24 MeV of energy and is therefore difficult to detect. A BR of 10^{-3} would obliterate the tagging for CP studies. Theoretical predictions¹⁰ range from 10^{-4} to 10^{-6} . If the ϕ is boosted (to 18 GeV in E852) then the radiated photon can have up to 1 GeV of energy. We should see about 400 decays of $\phi \rightarrow a_0 \gamma \rightarrow K^+ K^- \gamma$ if the BR is of order 10^{-3} . The a_0 can also decay into $\eta \pi^0$. At this level we should see 2000 decays:

$$\phi \rightarrow a_0 \gamma \rightarrow \eta \pi^0 \gamma \rightarrow 5 \gamma.$$

- ¹ Lindenbaum *et al.*, BNL Experiment E881, 1991.
- ² F. Binon *et al.*, Nuov. Cim. **A78** (1983) 313; F. Binon *et al.*, Nuov. Cim. **A80** (1984) 715; F. Binon *et al.*, Phys. Lett. **182B**.
- ³ S. Gershtein *et al.*, Z. fur Phys. C24 (1984) 305.
- ⁴ C. Amsler *et al.*, CERN-PPE/91-188 (1991).
- ⁵ D. Alde *et al.*, Phys. Lett. **205B** (1988) 397; M. Boutemour, Proceedings of the BNL Workshop on Glueballs, Hybrids and Exotics, S. U. Chung, ed. American Institute of Physics Proceedings No. 185 (1989).
- ⁶ Review of Particle Properties, Phys Letters **239B** (1990).
- ⁷ Our estimates are based on a 2000 hour run sensitivity of 2.88 events/pb and a $15 \mu\text{b}$ inclusive ϕ cross section measured by B. Ghidini *et al.*, Phys. Lett **68B** (1977) 186.
- ⁸ J. Rosner, Phys Rev **D27** (1983) 1101.
- ⁹ G. Barbiellini *et al.*, Particle World Vol 1 No. 5 (1990) 138 and references therein.
- ¹⁰ S. Nussinov and T. Truong, Phys Rev Lett **63** (1989) 1349; J. Lucio and J. Pestieau, Phys Rev **D42** (1990) 3253; D. Cocolicchio *et al.*, Phys Lett **B238** (1990) 417; N. Paver and Riazuddin, Phys. Lett **B246** (1990) 240; N. Brown and F. E. Close RAL-91-085 Preprint.

The E852 Apparatus

Overview

The E852 apparatus is shown in Fig 5. The 30-cm liquid hydrogen target is in the middle of the MPS magnet. The drift chambers sit in the magnetic field. Drift chambers TDXA,B are being built by the BNL group. The segmented Cerenkov counter, C8, will be built by BNL and SMU. C8 will not be in place for the initial data-taking in 1993 but will be installed in 1994. The target region is shown in detail in Fig 6. A cylindrical drift chamber, TCYL, has been built by SMU. This chamber will detect charged recoils. A soft-photon detection system (CIA,

CIB and DEA) will tag events with recoil photons which miss the LGD. The primary source of these photons are recoil baryon resonances which decay into $n\pi^0 \rightarrow n2\gamma$. For all-neutral triggers the missing mass resolution is inadequate to distinguish these events from events with a single recoil neutron. The PWA requires knowledge of the recoil system. The CIA and CIB are part of the CsI barrel (see Fig 7) being constructed by UND. At this writing, 54 of the 180 crystals are on hand. The DEA, shown in Fig 8, is a lead/scintillator photon detector and is being constructed by SMU and BNL. The data acquisition system is being designed and assembled by the BNL group.

FIG.1 : E852 schematic Layout

CIA	Cesium Iodide Endcap (18 elements)	DCM1...6	MPS Drift Chambers
CIB	Cesium Iodide Barrel (162 elements)	TPX2	Proportional Wire chamber(672 sense wires)
TCYL	Cylindrical Drift Chamber (4 gaps and 252 sense wires)	BV	Beam Veto ctr. (Scintillation counter)
CPVA,B,C	Scintillation counters	C 8	Threshold Cerenkov counter (11 cells)
TPXA,B	Proportional Wire Chamber (2 planes 800 sense wires)	TDXA,B	Drift Chamber (2 planes and 384 sense wires)
DEA	Lead-Scintillator sandwich	EV	Elastic Veto (Scintillation counters)
		LGD	Pb-Glass Detector (3053 4x4 cm elements)

Fig 5: Schematic Layout of E852

Fig. 2 : E852 Target Region (Elevation View)

Fig 6: Detail of the E852 Target Region

Fig 7: The CsI Barrel

Fig 8: The Downstream Endcap (DEA) Lead/Scintillator Veto

The LGD

The lead glass detector is shown in Fig 9. It consists of 3053 modules arranged in 71 columns and 43 rows. The LGD front face will be located 5 m downstream of target center. Each module consists of a lead glass block (4 cm by 4 cm x 45 cm), a FEU-84-3 PM and a Cockcroft-Walton base. The glass and PM's are being supplied by IHEP and the bases by MSU. A photo of a module assembly is shown in Fig 10.

The glass has a radiation length of 3 cm. The total weight of glass, PM's and bases is about 11 tons. The array will be placed in a frame shown in the photo of Fig 11. This frame will move vertically in an outer structure, the base of which is shown in the photo of Fig 12. The latter will move horizontally. The vertical and horizontal motion, controlled by computer, will allow us to place each module into the electron beam for calibration. This transporter system will have a position accuracy of 1 mm, a horizontal speed of 1 cm/sec and a vertical speed of 0.5 cm/sec. The

Fig 9: A Schematic Drawing of the LGD Detector.

Fig 10: The Glass/PM/Cockcroft-Walton Base Assembly

Fig 11: Vic Matesson, IU machinist, standing inside the frame which will eventually hold the 3050 lead glass blocks. This assembly will move vertically within another assembly by means of the two vertical jack screws on either side of the frame. Vertical speed will be about 5 mm/sec.

Fig 12: This base assembly is for the outer structure within which the frame and glass will move. The outer assembly will move horizontally on rails. One of the wheels can be seen resting on the base assembly.

entire structure is being made of steel to provide some shielding for the PM's from the effect of the MPS fringe field, which can be as large as 100 gauss. The PM's will also have soft-iron and μ -metal jackets to serve as additional shielding against the fringe field. The PM's and bases will be registered with respect to the glass by a cellular wall of 3053 holes. The transporter will also have a Faraday cage for the signal cables to the ADC's. An electronics trailer for the ADC's, trigger electronics and HV system will reside atop the transporter. Our goal is to install the transporter, which is being manufactured in the IU machine shop, in the MPS by early fall. At that time the field will be measured to ascertain the field at the position of the tubes and to

understand how the presence of the transporter distorts the fringe field for tracking purposes.

Acceptance

The acceptance for all-neutral final states is shown in Fig 13 as a function of mass for various combinations of π^0 , η , ω . In estimating the acceptance we require all photons to enter the LGD, all photons to have more than 0.5 GeV of energy and that they be separated by at least 8 cm. The acceptance in the Gottfried-Jackson decay angular variables is shown in Fig 14 for an $\eta\pi^0$ system of mass 1.4 GeV (the $J^{PC} = 1^{-+}$ exotic mass). The acceptance is adequate to allow for a proper PWA.

Fig 13: Acceptance as a Function of Mass for Various All-Neutral States

Mass = 1.4 GeV; Full LGD

Fig 14: Acceptance in the Gottfried-Jackson Angular Decay Variables

Quality Control

Having a detector with 3000 modules requires that strict quality control be exercised. IHEP has already shipped the glass (see the photo of Fig 15) and PM's to Bloomington. A computer-controlled block measurer was built to measure the dimensions of the blocks. This device is shown in the photos of Figs 16 and 17. Approximately 1500 blocks have been measured to date. The distribution of thickness and taper for about 1000 blocks are shown in Fig 18. The blocks meet the transverse dimension specifications of $\pm 50 \mu$. We expect to complete the block measuring in 1992.

In order to evaluate the PM's, a computer-controlled system was designed to measure

relative quantum efficiency, total noise and correlated noise. A schematic of the device is shown in Fig 19 for single-tube measurements and a photo of the device is shown in Fig 20 for a four-tube setup. The idea is to have an americium source embedded in a scintillator and viewed by a reference (trigger) tube. The tube under test is located a sufficient distance away as to have a low enough counting rate so that the mean number of photoelectrons can be determined from the inefficiency (using Poisson statistics). Each tube under test is placed in the same location so that the acceptance for photons stays constant from tube to tube. Three tubes (high, medium and low efficiency) were sent to Hamamatsu for an absolute measurement of the quantum efficiency. This provides the calibration of the system. The distribution in quantum efficiencies is shown in Fig 21 for 1000 tubes.

The results are excellent. The remainder of the tubes will be graded by the end of 1992.

Prototype LGD's: P1 and P2

Before embarking on the full LGD we decided to build two prototype LGD's at approximately 1/100 and 1/10 of the scale of the final LGD. We name these prototypes P1 and P2. The former is a 25-element device which was tested using cosmic rays and the A2 beam at BNL. The results are described below. P2 is a 18 x 18 = 324 stack which will be tested using a 15 GeV π beam in the A3 line in May and June of 1992. The goals of these tests will be described below.

Prototype P1

A 25-element prototype was assembled in early 1991. A photo is shown in Fig 22. P1 was used to take data with cosmic rays in January, 1991 and these tests immediately pointed out a problem with the scheme of coupling the PM to the glass using a Sylgard cookie. This problem was corrected before the tests in April and June of 1991 in the A2 line. Those tests were a success. Our resolution was measured as:

$$\frac{\sigma}{E(\text{GeV})} = \left[1.2 + \frac{5.1}{\sqrt{E(\text{GeV})}} \right] \%$$

Fig 15: Crates containing 3200 Lead Glass Blocks now in Bloomington

Fig 16: (to left) The Computer-Controlled Block Measurer Used to Measure the Thickness of Lead Glass Blocks along the Length of the Block

Fig 17: (below) A closeup of the Measuring Stage. The four pneumatically-driven sensors push up against the block and provide two thickness measurements.

Fig 18a: Distribution of Thickness Measurements of ≈ 1000 Lead Glass Blocks

Fig 18b: Distribution of Taper Measurements of ≈ 1000 Lead Glass Blocks

Fig 19: Schematic of the PM Measuring Device. This setup is used to measure quantum efficiency, correlated noise and total noise

Fig 20: The four-tube PM Measuring Station

Fig 21: Distribution of Quantum Efficiencies of ≈ 1000 PM's at 1900 V

using 0.5, 1.0, 3.0 and 5.0 GeV electrons (see Fig 23). We also measured the effect on the central energy and width (sigma) by placing pre-radiators in front of P1. These results are shown in Table 1. The effect of non-normal incidence was also studied at the extremes of the final LGD. The effect on the central energy and width (sigma) is small (see Fig 24). Finally a variable, F, which measures the transverse spread of the shower can be used to distinguish electrons from pions. The distribution in F, given by:

$$F = \frac{\sum_{j=1}^{25} E_j \sqrt{(x_j - \langle x \rangle)^2 + (y_j - \langle y \rangle)^2}}{\sum_{j=1}^{25} E_j}$$

$$\langle x \rangle = \frac{\sum_{j=1}^{25} E_j x_j}{\sum_{j=1}^{25} E_j}$$

$$\langle y \rangle = \frac{\sum_{j=1}^{25} E_j y_j}{\sum_{j=1}^{25} E_j}$$

is shown in Fig 25. In principle F can be computed within the trigger processor algorithm to provide online e/π separation.

The prototype P1, viewing cosmic rays, has also been used for checking out alternative PM-glass coupling schemes, for electronic check out and for long-term stability measurements.

Fig 22: A 25-element LGD similar to the one used in the A2 tests last year. The cover, which is normally in place, has been removed for this picture.

Fig 23: The energy resolution of P1 as measured in the A2 tests

Beam Energy (GeV)	Pre-Radiator Thickness (RL)	ΔE (MeV)	$\sigma = a \cdot \sigma_0$ $a =$
1	0.6	30	≈ 1
1	1.7	100	1.20
3	0.6	40	≈ 1
3	1.7	180	1.12

Table 1: Effect of placing pre-radiators in front of the P1 LGD

Fig 24a: The mean value(GeV) of the energy distribution as a function of angle of beam incidence (degrees)

Fig 24b: The standard deviation (GeV) of the energy distribution as a function of angle of beam incidence (degrees)

Fig 25: Distribution of the F variable used to measure transverse shower size

Prototype P2

Prototype P2 is an $18 \times 18 = 324$ module array which is schematically shown in Fig 26. The box, lid and cellular wall were fabricated in the Notre Dame machine shop. This structure has a transporter system shown in the photo of Fig 27. Our original goal was to use the final LGD housing/transporter for the A3 tests but it became clear earlier this year that it would not be completed in time. Luckily we found a transporter owned by Kyoto University in Japan. Prof. Masaike, of Kyoto, kindly let us borrow the transporter. This transporter has been outfitted with the motor, control system and position readout system to be used in the final LGD transporter. We will have an opportunity to exercise this system during the A3 tests as we calibrate P2. For monitoring we will use a nitrogen laser which will be used to launch light into a light distribution system partially shown in the photo of Fig 28.

P2 will be used in tests in the A3 beam line during May and June of 1992. There are several goals of this tests which will utilize a 5 GeV electron beam and a 15 GeV pion beam. The first goal is to exercise the calibration algorithm. This will involve placing each module under computer control into the electron beam. This will also be the first opportunity of a serious field test of the custom-built ADC's (more on that below). We have built trigger modules for this test which will require that n of m modules have an energy between two limits. This will be used to optimize the trigger for collecting events of the type:

$$\pi^- p \rightarrow K_s^0 X \rightarrow \pi^0 \pi^0 X \rightarrow 4\gamma X$$

This should give us a rich sample of multi-photon events, highly constrained, which will then allow us to design our trigger processor algorithm. We will also run with triggers requiring one or two charged particles into the LGD along with photons. These data will again guide

us in developing algorithms for hadron/photon separation. We expect to run for 200 of data-taking with a 15 GeV pion beam and 50 hours of calibrating with a 5 GeV electron beam.

Fig 26: A schematic drawing of the P2 assembly. The box, lid and cellular wall were fabricated by the Notre Dame machine shop.

Fig 27: This photo shows the P2 box sitting atop the transporter which was borrowed from Prof. Masaike of Kyoto University. This transporter has been outfitted with the motors and control system to be used for the final LGD transporter.

Fig 28: This is a portion of the light distribution system for P2 monitoring. Laser light is launched, using optical fibers, into two bars, each with 18 nipples. These are then used to launch light into 18 other bars, each with 18 nipples placed in contact with the glass blocks.

Custom-Built ADC's

It has become clear from other experiments that final states with π^0 , η , ω , η' provide a fertile hunting ground for $non - q\bar{q}$ mesons. The experimental challenge is to collect an enriched sample of such events. This requires the development of a trigger processor to identify photon showers, their energies and locations and to calculate effective masses. These operations need to be done in about $15 \mu\text{sec}$ to avoid serious deadtimes. We know, from our dimuon trigger experience in Fermilab experiment 672, that these calculations can be executed in about 7 to $10 \mu\text{sec}$. This means that the ADC's must digitize and present their output to the trigger processor in about $5 \mu\text{sec}$. It is also important that the number of bits be sufficient for photon energy and spatial resolution. Commercially available ADC's are not up to the task either in speed or number of bits (see Table 2). We have therefore developed custom-built ADC's for E852.

A schematic of the custom-built, 12-bit ADC design is shown in Fig 29. These ADC's will eventually be packaged as FASTBUS modules with 32 channels per module. For the P2 tests, these ADC's are packaged in CAMAC modules, 16 channels per module. The heart of the ADC is the front end integrator (see the photo of Fig 30) which holds the signal, does a background subtraction, and presents the background-subtracted signal to two discriminators and the digitizer. The outputs of the discriminators, each with their own threshold, are available for a first-level trigger (e.g. multiplicity counting). The background subtraction feature provides noise immunity from DC to $\approx 1 \text{ KHz}$. The time required for digitization is $4 \mu\text{sec}$. Tests have shown that the integrated non-linearity is about 1 part in 4096. The reset time is 250 ns, an important feature, for deadtime considerations, if we plan to run at higher pre-trigger rates. A photo of a 16 channel CAMAC ADC module is shown in Fig 31.

Fig 29: Schematic of the custom-built ADC design for E852

Type	Phillips 10C2	LeCroy FERA	IU Custom
package/channels	Fastbus/32	CAMAC/16	Fastbus/32
bits	10	11	12
conversion time	7.0 μ S	8.5 μ S	4 μ S
readout for 100 words	2.5 μ S	12.5 μ S	2.5 μ S
reset time	0.5 μ S	2.0 μ S	0.25 μ S
on board disc.	NO	NO	YES
DC & AC noise rej.	NO	NO	YES
on board calib.	1/4 scale only	full range	full range
cost/chan	\$149	\$154	~\$150

Table 2: Comparison of E852 custom-built ADC's with commercial ADC's

In order to construct these modules a factory has been setup in the HEP lab on the Bloomington campus. Surface mount technology is used. A SciCards design program is used for multi-layer board layout. The output is sent to a company which produces the boards. Components are placed on boards and soldered in the ADC factory. Twenty CAMAC modules (or a total of 320 channels) will be ready for the P2 tests. Components of the factory are shown in the photos of Figs 32 through 35.

Conclusions

Physics

E852 is a position to make significant contributions to the experimental challenge of light-quark spectroscopy: where are the *non* - $q\bar{q}$ mesons? In the discussion presented earlier only a few of the issues were discussed. Complementary measurements are being made at LEAR, GAMS and in J/ψ radiative decay experiments. BNL is in the position of being able to make unique contributions because of the energy regime of the AGS and the high-intensity secondary beams. This coupled with the technology of E852 means the discovery potential is great.

Technology

A great deal of effort has gone into upgrading the MPS to meet the physics challenge. The additional tracking, Csl barrel, DEA, C2, LGD and the data acquisition system are important improvements. The trigger processor and ADC's associated with the LGD effort make E852 a unique experiment in light-quark spectroscopy.

Progress

We have imposed deadlines on ourselves to make sure that possible problems with the LGD and electronics design are uncovered as early as possible. The P1 prototype exercise was a success. P2 is now being placed on the AGS floor. The major components are in a state of readiness for beam. We expect to learn a lot from the data of the P2 run. The quality control work is thorough and will be completed by the end of 1992. The assembly of the LGD, its transporter and electronics, will be completed in time for preliminary data-taking in 1993.

Sociology

Since Notre Dame and Indiana are only 200 miles apart our two groups have frequent meetings. Between our two institutions, eight students are involved. These students have the opportunity to be involved in design, construction and testing and in many cases are part of the decision making. Chris Davis from U. of Louisville makes frequent trips to Bloomington to discuss software projects for E852. Andrei Demianov from Moscow State is being supported by the U. of Louisville and is in residence in Bloomington. He has worked on the construction of the P2 housing and is now working on the PM HV/base system.

At Indiana, nine researchers are involved almost full-time in E852. We have regular weekly meetings and other informal meetings several times a week. Several machinists are involved in the construction of the transporter, the largest piece of equipment built by our machine shop. Three technicians have been employed in quality control and electronics construction. We have and will continue to involve undergraduates in E852 activities. We have received generous support from the University in personnel support and matching equipment funds (\$60,000 to date). We also make use of two lab rooms, the old cyclotron area, and the hi-bay area for construction, testing and quality control. It is important for us to keep the level of on-campus activity high. We make an effort to do as much work as possible in Bloomington before moving equipment to BNL. This means reduced travel and the visibility makes it possible to attract excellent students.

Fig 30: ADC Integrator Board: This is the surface-mount daughter board for one ADC integrator. This board performs an integrate-and-hold with background rejection and provides two levels of discrimination. The components are installed in Bloomington using the ADC factory.

Fig 31: CAMAC ADC Board: This mother card accepts 16 of the integrator cards. In the final system, 32 ADC channels will be mounted in FASTBUS boards.

Fig 32: Solder stencil printer: The stencil for the CAMAC board is shown. This tool is used to deposit small amounts of solder paste onto the boards.

Fig 33: Pick-and-Place Machine: This is used to select components from a "lazy susan" tray which are then picked up with a vacuum tool and placed on the board.

Fig 34: Infrared Reflow Oven: First the solder paste is applied to the boards, then the components are placed onto the boards and finally the board is placed in this oven to melt the solder.

Fig 35: Hot air Tools: These are used for replacing components and for installing pins on the daughter edge cards.

Superconducting Super Collider

1. Solenoidal Detector Collaboration

Introduction

On December 16, 1990, the Program Advisory Committee at the SSC Laboratory approved the Solenoidal Detector Collaboration (SDC) to proceed to the detector design stage. Our group at Indiana University participated in writing the Conceptual Design Report for the Straw Tracking System and the Technical Design Report for Solenoidal Detector Collaboration (SDC) and helped defend the proposal to the PAC. Members of our group have been on the Executive Board, the Institutional Board, and several steering committees. We have been very active in the research and development of straw tube drift chambers for use in the SDC. The major part of this detector work and a substantial tracking simulation effort are ongoing as part of the SSC Wire Tracking Subsystem.

Personnel

The members of Indiana High Energy Physics Group who are in the SDC collaboration are:

Gail Hanson- past member of the Executive Board of the SDC

Harold Ogren- Institutional Board member

Alex Dzierba, faculty

Ben Brabson, faculty

Andrzej Ziemiński, faculty

Tom Marshall, Research physicist

Daria Ziemińska, Research physicist

David Rust, Senior Scientist, Leader of the Straw Electronics Working Group

Fred Luehring, Physicist/Programmer

Ellsworth Wente, Assistant research scientist

Bryan Martin, Technician

Tim Collins, Programmer- designer

The SDC Collaboration

The SDC grew out of several initially independent efforts centered at the Lawrence Berkeley Laboratory, Argonne National Laboratory, Fermilab, and the KEK National Laboratory in Japan, with strong participation from university groups. These efforts were all aimed at a solenoidal detector for high- pT physics at the SSC. At a workshop at Fermilab in September 1989, the various groups decided to combine their activities and develop a joint Expression of Interest for an SSC detector. An interim steering committee was set up to prepare a governance document and determine the membership of the collaboration. The collaboration was formally formed at the first collaboration meeting at Fermilab in December 1989. Presently the SDC consists of about 600 physicists from 11 different countries. In the Spring of 1990 the collaboration prepared and submitted an Expression of Interest (EOI) which outlined many of the details of the detector and areas of particle physics that could be explored. In June, 1990, the Program Advisory Committee at the SSC Laboratory indicated their approval of the SDC Expression of Interest and directed the collaboration to proceed to the writing of the Letter of Intent. This Letter of Intent (LOI) was reviewed by the PAC in November 1990. In December of 1990 the PAC approved the SDC experiment to proceed to the design stage. SDC was the only detector at that time to be given approval.

A major part of our effort this year was the creation of the Conceptual Design Report for the Straw Module Outer tracker. This report was reviewed in November, 1991 and January, 1992. The tracker working group recommended that the Straw Module Outer Tracker concept be accepted for the baseline design of the SDC. Our group at Indiana headed by G. Hanson also wrote the Straw Tracker section of the Technical Design Report. It was submitted April 1, 1992. Members of our group are also part of the core effort to develop a simulation of the SDC tracking system. We have been active in working with the technical board, the tracking task force, the Cost and Schedule group, and the facilities task force in the preparation for the design report.

The SDC Detector

One of the reasons for proposing a general-purpose detector for the SSC is provided by the great success of existing large detectors at electron-positron and proton-antiproton colliders. Many of the possible physics signals of interest at the SSC produce leptons and hadron jets at large angles and with large transverse momenta. It is thus natural to consider a detector that combines a large solenoidal magnet for determining the momenta

of charged particles with a hermetic calorimeter to measure jet and electron energies and missing transverse energy. The measurement of momenta with a magnetic field has the outstanding advantage of providing an absolute, stable energy scale. This is not easily achieved with calorimetric techniques. Moreover, the signs of charged particles can be determined, a capability that is essential for a number of physics topics such as charge asymmetries and like-sign dilepton production. A solenoid field configuration provides azimuthal symmetry and simplifies detector construction and event analysis. The detector envisioned for SSC, shown in Fig.1, consists therefore of a solenoidal spectrometer surrounded by electromagnetic shower counters, hadronic calorimeters, and systems for detecting muons.

It is the goal of the SDC to build a tracking system that will provide momentum measurements of all charged particles with p_T above a few GeV/c for $|\eta| < 2.8$. The tracking system will also provide a fast trigger for such particles. These goals can best be realized by several different types of tracking technology. The tracking detector will use a combination of silicon devices with wire chambers and/or scintillating fibers. For the region with radii greater than 80 cm the Straw Modular tracker is the baseline design. This tracker can provide a fast trigger for particles above some minimum p_T by the simple requirement that the reconstructed track segment in two of the three trigger layers be a high momentum track. They also provide significant pattern recognition and momentum measurement capability. A forward tracking detector called the Intermediate Track Detector that uses silicon microstrip technology is part of the baseline design.

SDC Related Activities of Indiana Members

1) Tracking Steering Committee

As one of the principle proponents of a wire tracking scheme using straw drift chambers, our group at Indiana is a significant force in the Tracking Steering Committee. We have finished a baseline design for straw tracking that is the basis of an engineering and cost study for the Technical Design Report. There are a multitude of areas that need to be optimized in the tracking design, such as material in the tracking region, pattern recognition with a mixed system, alignment and precision for components, electronics capabilities, safety concerns, and assembly and access requirements. Many of these topics require professional engineering studies and large systems experience. For this reason, some of this work is being coordinated through the Westinghouse Science and Technology Center and Oak Ridge National Laboratory.

2) Simulation group

The SDC tracking system will involve several types of detectors-silicon strips, scintillating fibers or straw tubes, and gas microstrip detectors. There are many parameters that define the tracking system such as track position measurement resolution, track separation capability, the average number of hit cells per event, the amount of material along a typical track, radial position of the layers, etc. A detailed simulation effort is required to optimize the tracking system. This is now proceeding for the straw tube system as a joint effort between Indiana University, University Colorado, and SCRI. Our group has supplied much of the code which simulates the straw tube system. Members of our group have helped form a unified simulation group and have studied the entire SDC tracking system for a variety of proposed tracking system detector arrangements. These studies are now preformed with the standard SDC simulation program, SDCSIM. Among the issues studied are tracking system resolution, pattern recognition ability, and occupancy.

3) Facilities

Members of our group are also part of the facilities task force. This group will specify the above-ground and below-ground facilities for the SDC. This work also includes specification of the assembly areas and the procedures for assembling straw chambers at the SSCL site.

4) Integration group

The Indiana group has assisted in the integration planning for the SDC Detector. This includes time scheduling, interaction hall requirements, support facilities, and SSC assembly structures, to name a few.

5) Collaboration Meetings

In addition to the above activities with the SDC collaboration our group has participated in a number of national and international meetings on SSC detectors.

The group has attended numerous meetings in the past year concerning the design of the SDC detector which was recently submitted in the form of the Technical Design Report. The meeting are listed at the end of this section. In the past year the following meetings of the collaboration were attended by members of the Indiana group.

May 13-16,1991	Collaboration Meeting at KEK in Japan
June 22,1991	Executive Board Meeting
Aug. 5-11,1991	Collaboration Meeting at Berkeley
Sept. 26-28,1991	Collaboration Meeting at ORNL
Nov. 10-16 ,1991	Collaboration Meeting at SSCL
Jan.8-11,1992	Collaboration Meeting at Pisa
Feb 26-29,1992	Collaboration Meeting at SSCL
April 9-12,1992	Collaboration Meeting at FNAL

2. SDC Modular Straw Group

Introduction

Indiana has led the effort to design a drift chamber tracking system inside the SDC in the 8 meter long cylindrical volume from 0.8 to 1.7 meters from the interaction point. The group has chosen straw tube drift cells as the basis for this tracking system and has designed and built prototype units or modules very close to the specifications necessary for the SDC detector.

Other groups which have been collaborating in this effort are University of Colorado, University of Pennsylvania, KEK National Laboratory (Japan), University of Michigan, Duke University, Westinghouse Science and Technology Center, Oak Ridge National Laboratory and Quantum Research Services.

The people at Indiana University working on this project are:

G. Hanson	Faculty,
H. Ogren	Faculty, Interim Leader of the Straw Group
D. Rust	Senior Scientist, Leader of the Electronics Group
F. Luehring	Physicist/Programmer,
T. Collins	Engineer/Designer and
E. Wente	Assistant Research Scientist.

The coordination of the project lies mainly with Indiana University and involves close communication with the other collaborating institutions. Meetings are held on the average of about twice a month sometimes in conjunction with the SDC collaboration Meetings. A great deal of communication is also carried on by electronic mail, telephone and FAX. The following is a list of the meetings attended by members of the Indiana Staff during the past reporting year.

Meetings attended for SDC related activities

April 16, 1991 - SDC Outer Tracking Engineering Meeting, Fermilab - Hanson, Ogren

May 2, 1991 - SDC Straw Electronics Meeting, University of Pennsylvania - Rust

May 7, 1991- SDC Straw Placement Meeting, Duke University - Hanson, Ogren

May 13-16, 1991 - SDC Collaboration Meeting, KEK - Hanson, Ogren, Rust

May 29, 1991 - SDC Straw Placement Engineering Review, SSCL - Foster, Hanson, Ogren, Rust

May 30-June 1, 1991 - SDC Tracking Simulation, Physics and Detector Performance Meetings, SSCL - Hanson, Luehring, Luo

June 5-6, 1991 - SDC Costing Meeting, Lawrence Berkeley Laboratory - Ogren

June 19-22, 1991 - SDC Tracking Material Task Force, Collaboration Meetings, SSCL - Hanson, Luehring

August 5-10, 1991 - SDC Collaboration Meeting, LBL, Berkeley, California - Hanson, Luehring

August 21-25, 1991 - Composites Horizons, Covina, California (module shell) - Ogren

September 4-5, 1991 -1991: Composites Horizons, Covina, California (module shell) -Ogren

September 6-7, 1991 -Straw Tracking Subsystem Meeting, University of Colorado, Boulder, Colorado - Foster, Hanson, Ogren, Rust

September 10, 1991 - RTI Plastics, Minneapolis, Minnesota (wire supports) - Foster

September 26-28, 1991 - SDC Collaboration Meeting, Oak Ridge, Tennessee - Hanson, Luehring, Ogren, Rust, Wentz

October 10, 1991 - Composites Horizons, Inc. Covina, Ca Harold Ogren

October 21-23, 1991- SSCL, Simulation meeting, F. Luehring

November 19-20,1991 - Fort Wayne, In, PROengineering conference, R. Foster

November 10-16, 1991 - SSCL, SDC collaboration meeting, Ogren, Rust, Hanson,Luehring

December 4-6, 1991 - SSCL, Engineering review Ogren

December 11-12, 1991 - Hercules, Inc Salt Lake, and Composites Horizons,
Ogren

Jan 8-11, 1992, SDC Collaboration Meeting Pisa , Italy, H. Ogren, G.
Hanson

Jan 30-Feb 3, 1992 Tracking Evaluation Committee , SSCL H. Ogren, G
F. Luehring.

Feb 10-13, 1992 - Visit to Votaw, Century Design, CHI, California, Ogren

Feb 21-22, 1992 - Straw group meeting, Bloomington, IN

Feb 26-29, 1992 - SSC Collaboration Meeting Dallas, F. Luehring, T.
Collins, H. Ogren, D. Rust

March 12-13, 1992 - Straw Electronics meeting SSCL, D. Rust, H. Ogren

April 7, 1992 - Straw Electronics meeting, Indiana University

April 8-10, 1992 SDC Collaboration meeting, FNAL D. Rust, G. Hanson,
H. Ogren, T. Collins, E. Wente, F. Luehring

April 21, 1992 - Electronics and Structure Workshop, WSTC
D. Rust, T. Collins, H. Ogren

SDC Wire Chamber Tracking

The efforts of our group at Indiana have been in developing continuous cathode drift chambers. To meet the constraints imposed by radiation damage, current draw, chamber lifetime, gain reduction from large particle flux, hit rate, loss of data because of high occupancy, and pattern recognition in complex events, the cylindrical drift cells are made as small as practical. Acceptable current draw and lifetime can be obtained with a 4 mm diameter straw tube chamber about 50 cm from the beam line; the other operating limits are somewhat less restrictive. This is also the practical lower limit on the tube diameter from considerations of track ionization density and electrostatic stability. Occupancy is minimized by use of a fast gas such as a mixture containing CF₄.

The straw tubes have to be as long as 3 or 4 meters and this means they must be supported to keep them straight and in a precise and stable position. We have proposed that this can be accomplished by packing them in thin but rigid shells made from carbon fiber epoxy composite material. These modules would maintain the alignment of one tube with

respect to its neighbors in the module. The modules would then be aligned with respect to each other. The alignment of the 212/159 tubes in each module would be automatic due to the precise construction technique, and the total alignment task would consequently be reduced.

We have been working together with several other groups who have been contributing in several areas. The group from the University of Pennsylvania has developed a preamplifier and shaper circuit and has studied various triggering schemes. The preamplifier-shaper circuit is being adapted to larger scale integration. It may also be integrated with a discriminator circuit. This is a very important part of a wire chamber system because of the severe requirements dictated by the high rate, the needs for low noise and operation at low gain, low power consumption and also by the limited space.

Part of our 1990 proposal included justification for development of techniques for a gaseous charged track detector to cover the non-central (intermediate) rapidity range $1.4 < |\eta| < 2.4$ of a hadron supercollider experiment. Coverage of this rapidity range is extremely important for the best possible acceptance for new physics, and it is not easily accessible with sense wires oriented as in a conventional central track detector i.e, parallel to the beam axis. Called the Intermediate Track Detector (ITD), this tracker would use arrays of silicon microstrip detectors, mounted as disk shaped detectors in the forward regions of the tracking volume. This area of development was assumed by some groups from the UK - University of Liverpool, University of Glasgow, and the Rutherford Appleton Laboratory. The tracking design is shown in Fig. 2. The Conceptual Design report is attached as a reference document.

Prototype Construction

During this reporting period we have worked on three prototype chambers: a 64 straw module, a 1 meter full cross section module, and a 4 meter full cross section module.

64 Straw Module

We completed fabrication of six one-foot 64-straw modules, which were distributed to collaborators at University of Michigan, University of Colorado, KEK, and University of Pennsylvania for testing of trigger and electronics. These are complete working modules with straws, wires, end plates, gas and electrical connections. These were used for setting up data acquisition electronics, evaluations of resolution and efficiency.

1 meter full cross section prototype

Three carbon fiber Rohacell foam shells were fabricated by Composites Horizons, Inc. They investigated the use of an extra resin sheet in addition to the 3 lamina of 0.002 in carbon tape. They also constructed a shell using only two carbon fiber lamina and a resin sheet. The 1 meter module used the lightest density Rohacell foam, IG31. All shells had the required stiffness and straightness.

For the assembly of the 1 meter module, a straw clamping tool was designed and positioned on a flat rail bed and aligned to a straightness of 0.001 inches. The wire supports were inserted in the straws and a bundle of 159 straws was bonded together. With the same graphite tooling that was used for forming the shells, the straw bundle was enclosed in the bonded shell. All the 159 wires were strung by blowing a leader thread through the straws and wire supports and pulling the 25 micron wire back through the straw. The wires were tensioned at 50 grams and soldered. The wires were tension checked, the endplates were positioned and the array was leak checked. All wires were tested on the module, one signal wire connection was incomplete, but appears to be only a slight misalignment of the solder clip. 16 channels of the chamber were read out using a printed circuit board that employed the University of Pennsylvania amplifier chip. Using this small read out, the efficiency and the resolution of the chamber were studied. The measured efficiencies for cosmic rays appears to be near 100% for reasonable voltages.

4 meter Module Fabrication

The 4 meter shell design was finalized after testing the 1 meter shell. The first shell from Composite Horizons was received on January 12, 1992. A number of thickness tests were made on this shell, to establish whether it is was within specifications. The shell lid and base were bonded together. The resulting module was subjected to a number of tests to verify the engineering calculations. We measured the deflection under gravity and with a three point bending test. We also subjected the shell to a 30 lb force load and monitored the shell for deflections. These measurements agreed quite closely with the predictions.

A new type of straw using a Kapton material with 1500 Å of copper was used for the four meter straws for the first time. The straws were measured to have a resistance of 130 ohm, a little larger than was expected. A technique was developed for inserting the 6 double V's in each straw and gluing them with super glue. At the same time that the double V's were inserted a leader line of mono-filament line was inserted to use for stringing the wires.

The second and third shells were received from Composite Horizons on March 25. They were measured and surveyed. The third shell was used for the final module. The first four meter long prototype module was completed on April 15. It is now undergoing testing. A cross section of the module is shown in Fig. 3.

Simulation effort

Computer simulation work at Indiana University has focused on several topics: simulation of the detector geometry, evaluating the performance of the detectors, pattern recognition and track fitting studies, and simulation of our detectors within a simulation of the entire SDC detector. This work was done in the context of the SDC collaboration simulation program, SDCSIM using a DEC VAX 6340 and two IBM RS/6000 workstations.

Both the VAX 6340 and RS/6000 computer systems now have installed on them the SDCSIM program which is a GEANT-based model of the entire SDC detector. The SDCSIM program has options built into it to allow comparison of the various detector design options. We have contributed to the collaboration-wide job of developing the SDCSIM program by writing command procedures that install it automatically on VAX-type computers. We use the SDCSIM program to investigate the performance of various tracking system configurations. The crucial issues of occupancy, measuring resolution, and pattern recognition have been studied at up to ten times the SSC design luminosity. In Fig.4 we show an event simulation of a combined strawtube, gas microstrip, and silicon tracking system.

Considerable effort has been put into studying how well the SDC tracking system will measure kinematical quantities like transverse momentum (P_T) and azimuthal angle (ϕ). These studies were made by running single tracks through the simulated SDC tracking system and reconstructing them. In order to gauge the effect of material, the studies were done in three conditions: (1) no interactions, (2) interacting muons, and (3) interacting electrons. The results are that for non-interacting particles the SDC tracking system meets its design specification and that the resolution degrades as one would expect when interactions are turned on. Fig. 5 shows a typical non-interacting particle P_T resolution.

Work continues on the pattern recognition procedure that matches track segments in azimuth and curvature. Since the full simulation of the geometry includes stereo superlayers, we are able to study the resolution of the tracking system in the coordinate along the wire direction. Our current pattern recognition algorithm finds stiff tracks well

for Higgs events where the decay mode is into muons. We have studied the effect of luminosity on pattern recognition and linked hits in the strawtube system with hits in the silicon system. The algorithm used is a global one that does not require a track to be found in just the silicon or just the straw tubes; the full pattern recognition capability of all parts of the tracking the system is used. This algorithm was used to find in excess of 90% of the Higgs decay muons at ten times the SSC design luminosity. Work is underway to extend this algorithm in linking hits found in the gas microstrip system which will provide coverage at higher luminosities.

Engineering Effort

The Indiana group has been working with the Westinghouse Science and Technology Center (D. T. Hackworth and R. L. Swensrud and their support personnel) to develop engineering concepts for the outer wire tracker. Westinghouse was selected to be the lead engineering group for the tracker support system, which includes the support cylinders and the spaceframe end supports. They have provided extensive engineering help calculating stresses, strains, deformation, etc. Our goal is to design a practical structure for supporting the straw tube modules. Engineering studies form a large part of the wire chamber tracking group effort because of the large size of the detector and the requirements of a minimum of mass and very high stability of the structure which hold the drift cells.

The engineering work on the carbon fiber shells which will hold the straw tubes is being done largely at Indiana University. We have hired an engineer/designer, Tim Collins, to assist us in this effort. WSTC has also helped with finite element analysis of the carbon fiber structure. They have completed a number of finite element analyses on prototype test modules and on the proposed 4 meter modules required for the final tracking system. This work will continue as the prototype development progresses.

The Westinghouse Science and Technology Center and Oak Ridge National Laboratory have also been working under our direction and as part of the Outer Straw Tracking Group on some detailed studies of several proposed concepts for mounting and supporting the chamber modules in a precise way. This has included a system which allows the modules to be removed and realigned as well as concepts that bond the modules to a rigid support frame early in the construction phase. We hope to be able to decide on a concept by this summer. Oak Ridge National Laboratory is the lead organization for the utilities and facilities for the outer tracker. They have been designing the cooling system and the electrical requirements.

Electronics

The group from the University of Pennsylvania (F. M. Newcomer, R. van Berg and H. H. Williams) has developed a low level, low power, high speed, low noise preamplifier shaper circuit. This circuit has been realized as a single channel in a surface mount package and has been available for about a year. We have been using a 16 channel board built to use these chips by John Oliver at Harvard. This has been available to us since the beginning of 1992. We have also just started to use a 16 channel board built by the University of Colorado using the same chips. These circuits have satisfied the design requirements for speed and noise. (See the SDC detector Technical Design Report.) The same circuit integrated with a tail cancelling circuit and a discriminator is now available with 8 channels in a single surface mount package. A 16 channel board using this new package will shortly be available and will be a definite step forward in the effort to make the electronics more compact.

The connection of the electronics to the chambers is a very important design problem and is being solved for our prototype modules by the University of Colorado and Oak Ridge National Laboratory. We have connection devices from Colorado that interface both our 159 tube modules and our earlier 64 tube modules to the 16 channel electronics boards. We expect soon to have from ORNL an even more compact arrangement of components for interfacing our 159 straw modules.

Basic Drift Chamber Research

Several developments in the design of straw tube drift chambers have been necessary in order to extend the concept to longer tubes, narrower tubes packed more densely, operation at higher repetition rate and operation in a higher radiation environment as is required for an SDC tracking system.

The longer tubes mean that the wire must be supported at regular intervals along the tube, and the attenuation length for a pulse traveling along the straw must be long enough that the pulse does not degrade severely. Wire supports have been designed to position the wire accurately approximately every 80 centimeters along the tube. These wire supports called "double-vees" have been available for more than a year now. Also tubes with thicker metalization have been developed to reduce the cathode resistance to about 25 ohm/meter, and the size of the anode wire has been increased to 38 microns or about 62 ohms/meter. The result is an attenuation length of 6.3 meters. Both of these developments together make long drift tubes practical.

The smaller diameter means that there is less ionization deposited in the tube and it is much more difficult to make electrical connections. This is solved partly by better electronics as described above. It is also helpful to use a drift gas which produces a large number of ionization electron clusters per unit length of a particle track. The mixture of tetrafluoromethane and isobutane (80:20) produces about twice as many clusters as argon based gases. We are still looking for improvements in gas mixtures partly to obtain better ionization yield but also , if possible, to eliminate the flammable gas.

The high repetition rate of the SSC means that a fast gas and short drift distance is necessary. Again the mixture of tetrafluoromethane and isobutane is recommended because the drift velocity is about 115 microns/nanosecond which is more than double the velocity of most argon based gases.

The same gas mixture is one of the key elements in the operation of a drift chamber over long time periods in relatively high radiation environments. It has been shown that there is no degradation of the gain due to deposits on the anode wire when a mixture of tetrafluoromethane and isobutane is used, and in fact there is a healing effect when this mixture is introduced into a chamber where the anode has become degraded. Another important element in producing a drift chamber which is tolerant of radiation effects is to make the cathode out of a conductive material other than aluminum. Carbon has been used in the past but in our application the cathode resistance must be lower than what can be obtained in this way. It has been found that noble metals such as gold and copper do not show the damage that is observed with cathodes made of aluminum. It has therefore been decided to use copper as the cathode material since gold has too short a radiation length.

All the requirements for straw tube operation at the SSC have been fulfilled as demonstrated by our studies. The best operating conditions will be determined in our future investigations.

PRESENTATIONS AND PUBLICATIONS ON SSC RELATED TOPICS

1992 Reporting period

Compression test of 4-meter module", T. Collins, Straw note #2, March 27, 1992.

" First results of 4-Meter shell measurements", H. Ogren, Straw note #1, March 27, 1992.

" Straw tracking system", H. Ogren ,SDC Technical and Executive Board Feb 2,3, 1992.

" Modular Straw Tracker" , H. Ogren, SDC Tracking Review Committee, Jan 30-Feb 2, 1992.

" Straw tracker Engineering Questions", H. Ogren, Pisa Italy, Jan 8-11, 1992.

" Straw-Silicon Simulation Studies" and
"Straw Tracking System" G. Hanson, Pisa, Italy, Jan 8-11, 1992.

Conceptual Design Report the Modular Straw Outer Tracking System
G. Hanson, et.al. IUHEE-91-10, SDC-91-00125 January 21,1992.

Technical Design Report Draft SDC-92-201 Feb 26,1992.

"SDC Modular Straw Outer Tracking System Conceptual Design Report" G. Hanson et.al. First Draft submitted to SDC Collaboration. SDC -91-00125.

" Design Report of the Outer Straw Tracker" talk by H. Ogren at the Technical Board meeting at SSCL, December 6, 1991.

" The Modular Tracker - Engineering aspects" talk by H. Ogren at the SSCL Engineering review at SSCL , December 5, 1991.

" Preliminary Simulation Results for the combined Silicon and straw tube Tracking System " talk by F. Luehring at the SDC Collaboration meeting at SSCL November 12, 1991.

"The Modular Straw tracker Conceptual Design Report" talk by H. Ogren at the SDC Collaboration meeting, November 11, 1991.

" SDC Simulation in a combined Silicon and Straw system" talk by F. Luehring at the SDC simulation meeting at SSCL October 21, 1991.

"Overview of Straw Tracking Design," talk by G. Hanson at SDC Collaboration Meeting, Oak Ridge, Tennessee, September 27, 1991.

"Progress in Simulating Combined Silicon and Straw Tube Tracking System," talk by F. Luehring at SDC Collaboration Meeting, Oak Ridge, Tennessee, September 26, 1991.

"SDC Simulation Program," talk by F. Luehring at SDC SHELL Workshop, IUPUI, Indianapolis, Indiana, September 6, 1991.

"Straw Module Status Report," talk by G. Hanson at SDC Collaboration Meeting, LBL, Berkeley, California, August 8, 1991.

"Progress in Simulating Straw Tracker," talk by F. Luehring at SDC Collaboration Meeting, LBL, Berkeley, California, August 5, 1991.

"Attenuation Studies of Straw Drift Tubes," E. Wente, D. R. Rust, B. Martin, H. O. Ogren, G. Hanson, and R. Foster, IUHEE-91-9.

"Review of Attenuation and Radiation Damage Studies on Straw Tubes," talk by D. Rust at SDC Collaboration Meeting, Oak Ridge, Tennessee, September 27, 1991.

"Recent Progress in the Design of a Hybrid Tracking System," talk by H. Ogren at SDC Collaboration Meeting, Oak Ridge, Tennessee, September 27, 1991.

"Central and Forward Tracking Collaboration: Progress Report for FY 1991," Subsystem Progress Report for SSCL, September 13, 1991 (copy included, contains the other reports as appendices).

"Proposal for Central Outer Tracking System," G. Hanson, F. Luehring, H. Ogren, and D. Rust, IUHEE-91-8, SDC-91-00061.

"Other Tracking Issues," talk by G. Hanson at SDC Tracking Material Task Force Meeting, SSCL, June 19, 1991.

"Self Centering Measurement for an 8 Layer Trapezoid," R. Foster *et al.*, IUHEE-91-7, SDC-91-00056.

"Overview of Tracking Simulation," talk by G. Hanson at SDC Physics and Detector Performance Meeting, SSCL, May 31, 1991. (copy not included).

"Progress in Simulating Straw Tracker, talk by F. Luehring at SDC Tracking Simulation Meeting, SSCL, May 30, 1991.

"Overview of Modules," presentation by H. Ogren at SDC Straw Placement Engineering Review, SSCL, May 29, 1991.

"Effects on Straw Drift Tubes of Extended Operation in a High Radiation Environment," D. R. Rust, IUHEE-91-1.

"Straw Placement," talk by H. Ogren at SDC Collaboration Meeting, KEK, May 13, 1991.

"Straw Tube Superlayer Design Concepts," University of Colorado, Duke University, Indiana University, Oak Ridge National Laboratory and Westinghouse Science and Technology Center.

1991 Reporting period

PROTOTYPE MODULE CONSTRUCTION- 64 STRAW RHOMBUS, H. Ogren, et al, IUHEE-91-1.

INVESTIGATION OF HIGH CURRENT LIMITATIONS OF ALUMINIZED STRAWS, D. Rust IUHEE-91-2.

ATTENUATION STUDIES FOR POLYCARBONATE AND KAPTON STRAWS: D. Rust, et al, IUHEE-91-3.

ALIGNMENT PRECISION REQUIRED FOR STRAW MODULES, H. Ogren, et al. IUHEE-91-4.

TRACKING IN THE SDC DETECTOR, G. Hanson, invited talk at the XXVIth Rencontres de Moriond, Electroweak Interactions and Unified Theories, Les Arcs, France, March 16, 1991.

EXPERIMENTS AT THE SUPERCONDUCTING SUPERCOLLIDER., G. Hanson. Indiana University- Purdue University at Indianapolis physics department colloquium, Feb. 21, 1991.

SSC UPDATE, H. Ogren, Indiana University Physics Department Colloquium, Jan 23, 1991.

RECENT DEVELOPMENTS IN STRAW DRIFT CHAMBER TRACKING AT SSC, H. Ogren, to appear in proceedings of Symposium on SSC Technology, Fort Worth, Texas, Oct 15-18, 1990.

DESIGN OF A TRACKING SYSTEM FOR THE SOLENOIDAL DETECTOR, G. Hanson, Symposium on Detector Research and Development for SSC. Fort Worth, Texas, October 15-18, 1990.

STRAW DRIFT CHAMBER UPDATE, H. Ogren, SDC Technology Review, Snowmass, Colorado, July 1-7, 1990.

A SOLENOIDAL DETECTOR FOR THE SSC, G. G. Hanson, High Energy Physics Seminar, University of Chicago, May 7, 1990.

RECENT DEVELOPMENTS IN 4 mm STRAW TUBES, H. Ogren, in Proceedings of the International Workshop on Solenoidal Detectors for the SSC, KEK, Tsukuba, Japan, April 23-25, 1990, p.

INTEGRATED TRACKING CONFIGURATION I: SILICON AND WIRE CHAMBERS, G. G. Hanson, in Proceedings of the International Workshop on Solenoidal Detectors for the SSC, KEK, Tsukuba, Japan, April 23-25, 1990, p.

STUDIES OF 4 mm DIAMETER STRAW TUBES, H. Ogren, Proceedings of the Workshop on Major SSC Detectors, Tucson, Arizona, February 18-23, 1990, p.217.

SIMULATION OF CENTRAL AND FORWARD TRACKING WITH WIRE CHAMBERS, G. G. Hanson, Proceedings of the Workshop on Major SSC Detectors, Tucson, Arizona, February 18-23, 1990, p. 596.

GAS STUDIES OF 4 mm DIAMETER STRAW DRIFT CHAMBERS, C. Neyman *et al.*, February, 1990, IUHEE 90-1.

WIRE STABILITY TESTS ON 4 mm STRAW CHAMBERS, H. Ogren *et al.*, February, 1990, IUHEE 90-2.

A WIRE SUPPORT DESIGN FOR STRAW DRIFT CHAMBERS, R. Foster *et al.*, February, 1990, IUHEE 90-3.

AN SSC OVERVIEW, G. G. Hanson, High Energy Physics Seminar, Indiana University, October 17, 1989.

SSC DETECTOR SUBSYSTEM PROPOSAL: CENTRAL AND FORWARD TRACKING WITH WIRE CHAMBERS, D. Blockus *et al.*, Proposal to the SSC Laboratory, October, 1989.

CENTRAL AND FORWARD TRACKING WITH WIRE CHAMBERS, G. G. Hanson, talk at the SSC Workshop on Solenoidal Magnetic Detectors, Fermilab, September 25-26, 1989.

TRACKING WITH WIRE CHAMBERS AT HIGH LUMINOSITIES, G. G. Hanson, Proceedings of the ECFA Study Week on Instrumentation Technology for High-Luminosity Hadron Colliders, Barcelona, Spain, September 14-21, 1989, p. 413.

REVIEW OF THE VANCOUVER WORKSHOP, D. Rust, High Energy Physics Seminar, Indiana University, September 12, 1989.

REPORT OF THE WIRE CHAMBER GROUP, G. G. Hanson, Proceedings of the Workshop on Tracking Systems for the Superconducting Supercollider, TRIUMF Laboratory, Vancouver, Canada, July 24-28, 1989, p. E15.

STRAW TUBE DRIFT CHAMBERS, H. Ogren, Proceedings of the Workshop on Tracking Systems for the Superconducting Supercollider, TRIUMF Laboratory, Vancouver, Canada, July 24-28, 1989, p. C145.

PHYSICS AND TRACKING REQUIREMENTS FOR 4p DETECTORS IN THE SSC ENVIRONMENT, G. G. Hanson, Proceedings of the Workshop on Tracking Systems for the Superconducting Supercollider, TRIUMF Laboratory, Vancouver, Canada, July 24-28, 1989, p. A23.

TRACKING GROUP REPORT, G. G. Hanson, talk at Solenoid Detector Meeting, De Soto, Texas, June 25-29, 1989.

SSC WIRE CHAMBER TRACKING, H. Ogren, talk at the Solenoidal Detector Meeting, Desoto, Texas, June 25-29, 1989.

Proceedings of the SSC Mini-Workshop on Tracking, Indiana University, Bloomington, Indiana, June 7-8, 1989, edited by A. Dzierba.

REQUIREMENTS FOR SSC TRACKING, G.G. Hanson, *ibid.*, p. 1.

STRAW CHAMBERS AT THE SSC, H. Ogren, *ibid.*, p. 19.

TRACKING WITH WIRE CHAMBERS AT THE SSC, G. G. Hanson, M. C. Gundy, and A. P. T. Palounek, to appear in Proceedings of the 4th Pisa Meeting on Advanced Detectors: Frontier Detectors for Frontier Physics, La Biodola, Isola d'Elba, Italy, May 21-26, 1989, SLAC-PUB-5041.

WIRE CHAMBER REQUIREMENTS AND TRACKING SIMULATION STUDIES FOR TRACKING SYSTEMS AT THE SUPERCONDUCTING SUPER COLLIDER, G. G. Hanson, B. B. Niczyporuk, and A. P. T. Palounek, Proceedings of the Wire Chamber Conference, Vienna, Austria, February 13-17, 1989, Nucl. Instr. and Meth. **A283**, 735 (1989).

TRIGGERING AND DATA ACQUISITION ASPECTS OF SSC TRACKING, G.G. Hanson, B. B. Niczyporuk, and A. P. T. Palounek, Proceedings of the Workshop on Triggering and Data Acquisition for Experiments at the Supercollider, Toronto, Canada, January 16-19, 1989, p. 55.

Fig. 1 The SDC detector , showing the external muon system, the calorimeter, and the internal tracking system.

Fig. 2 The Straw Outer Tracking system, showing the support structure that supports the 4 meter long straw modules.

Fig. 4. The simulation of of a Higgs event in the SDC tracker.

Fig. 5 . The P_t resolution of a non-interacting 500 GeV/c particle in the SDC tracking system.

END

**DATE
FILMED**

12 / 18 / 92