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HIGH ENERGY ACCELERATOR AND
COLLIDING BEAM USER GROUP**

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MASTER

Introduction

This is the initial year for our new grant with the U.S. Department of Energy (U.S. D.O.E. Grant No. DEFG05-91ER40670).

It has been an extremely productive year. Major results continue to be published by the OPAL experiment at LEP. LEP reached its peak design luminosity in June of 1991 and an additional 500,000 Z^0 events were observed by the end of the year.

This year we are continuing to publish results from the muon deep inelastic scattering experiment at Fermilab (E665). The final data run took place in early 1992 and the experiment is being dismantled (the large vertex magnet is being shipped back to CERN this summer). DØ at Fermilab is ready for data taking for the collider run at Fermilab in 1992.

We are members of the Solenoidal Detector Collaboration for the SSC and have made many contributions to the detector design. We are members of the SDC muon group as well as working on the R & D of a liquid argon calorimeter prototype that may be used for the SSC experiments. We have made major contributions to SDC software development.

We continued to have minor involvements in physics at Los Alamos (CYGNUS) and other esoterica.

The University of Maryland High Energy Physics Group consists of ten faculty members:

- A. Baden (Drew) (Assistant Professor)
- A. Ball (Associate Research Scientist)
- C.Y. Chang (Professor)
- N.J. Hadley (Associate Professor)
- A. Jawahery (Hassan) (Assistant Professor)
- R.G. Kellogg (Associate Research Scientist)
- S. Kunori (Associate Research Scientist)
- A. Skuja (Professor)
- G.A. Snow (Professor)
- G.T. Zorn (Professor)

We currently support five post-doctoral physicists (two part-time):

- M. Foucher
- A. Lee, IV (until September 1992)
- K. Streets (part-time)
- W. Springer
- additional DØ post doc

We are supported by five professional and technical staff members:

- R. Bard (Electronics engineer - part time)
- J. Colmar (Electronics engineer)
- D. Fong (Physicist/Computer Support Systems)
- P. Goldey (Technician)
- W. Miller (Faculty Assistant for Technical Support)

as well as three administrative and secretarial staff members:

- B. Dunn (Administrative assistant - part time)
- S. Megonigal (secretary - part time)
- T. Williams (Accounting clerk - part time)

The administrative staff is partially supported by the University. In addition we get technical support through the departmental engineering group (some engineering work being directly supported by the University), as well as the departmental electronics and mechanical shops.

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Section A: The Study of e^+e^- Interactions

The University of Maryland High Energy Physics Group has had a long history of involvement in studying e^+e^- physics at storage rings. Professor Gus Zorn led the University of Maryland High Energy Physics Group into experiments with e^+e^- colliding beams first at ADONE in Frascati, then at SPEAR. These experiments were followed by larger efforts at PETRA with PLUTO (C. Y. Chang, R.G. Glasser, R. G. Kellogg, B. Sechi-Zorn, J.A.J. Skard, A. Skuja, and G. T. Zorn), and after its demise, with JADE (R.G. Glasser, B. Sechi-Zorn, J.A.J. Skard, and G. T. Zorn). The PETRA experiments produced the first direct experimental evidence for gluons, strong evidence that the b quark is a member of a weak isotopic doublet, information on the structure function of the photon, and detailed results on weak interaction processes, quantum chromodynamics, gamma gamma interactions and resonant states. The work on the PETRA experiments has now drawn to a close.

In 1982 the Maryland group became a member of the OPAL experiment at LEP. The senior personnel involved in the experiment from Maryland are A. Ball, C. Y. Chang, A. Jawahery, R. G. Kellogg, A. Skuja, G. A. Snow, and G. T. Zorn. This involvement has culminated in the outpouring of results from the 1989-1991 data runs of OPAL at LEP. A detailed description of our OPAL work and physics results for the past year will be presented.

In addition to working on OPAL, Prof. A. Jawahery in his first years at Maryland was also active in CLEO 1.5. Highlights of experimental results were presented in previous reports. His work on CLEO has been completed.

Finally, Prof. A. Skuja has been collaborating with Prof. L.N. Hand of Cornell in understanding the physical basis of transverse and longitudinal polarization of electrons and positrons in storage rings. This work will also be described briefly.

The OPAL experiment at LEP

Co-Investigators and Collaborators: A. Ball, C.Y. Chang, A. Jawahery, R.G. Kellogg, G.A. Snow, A. Skuja, and G.T. Zorn

I. Introduction

The Maryland High Energy Physics Group was the first in the U.S. to join OPAL and has been followed by the University of Chicago, University of California, Riverside and Indiana University. A small group at Oregon U. has also recently joined OPAL. The Maryland Group designed and built the small angle electromagnetic calorimeter which serves as the luminosity monitor for OPAL, and the barrel and endcap hadron calorimeter embedded in the iron return yoke of the OPAL magnet. We continue to bear major responsibilities for the operation of these two parts of OPAL, both of which have been upgraded for the eight bunch operation of LEP scheduled to begin in 1992. In addition a major addition is being built for the luminosity monitor at very small angles so that the luminosity can be measured with an accuracy approaching 0.1%.

The physics results already obtained by OPAL (and the three other LEP detectors) are quite impressive. These include: a precise determination of the mass of the Z^0 boson, allowing $M(Z^0)$ to join G_μ and α_{EM} as the three best known parameters of the Electroweak Theory; the determination that the number of light neutrinos in the universe is three; the exclusion of a Higgs scalar meson of mass ≤ 51 GeV; the precise determination of the QCD coupling constant, α_s , after checking that Quantum Chromodynamics is completely consistent with all experimental tests; the indirect determination of the range of possible values for the top quark mass from a detailed measurement of many physical quantities that are each logarithmically sensitive to m_{top} via one loop corrections; the determination of the Z^0 couplings to quarks and leptons; the negative results of searches for heavy leptons, heavy quarks, leptoquarks, neutral and charged supersymmetric particles and so on, thus implying that their existence is only possible if their masses are close to or larger than $M(Z^0)/2$.

The LEP project has been incredibly productive and it promises to continue to be very interesting. As a few million Z^0 's are collected by each detector in the 1992-94 time period, many very precise measurements will be made that can be used to search with much more precision for deviations from the standard model. The study of transversely polarized electrons and positrons is leading to a precise energy calibration of the LEP machine and will reduce the systematic error on $M(Z^0)$ substantially. New silicon vertex detectors will enhance the b-quark and τ lepton physics that can be carried out. Initial data with the first version of OPAL's silicon vertex detector has been obtained in 1991. Limits on rare decays of the Z^0 will be improved or the decays found. A more precise measurement of the Z^0 lineshape will also be possible again yielding an incredibly precise test of the standard model.

LEP II, which will reach a center of mass energy of ~ 190 GeV is scheduled to begin running in late 1994. This will allow a renewed search for the Higgs particle up to 80-90 GeV, supersymmetric particles, heavy quarks (if a heavy 4th family were to exist), and a detailed study of the reaction $e^+e^- \rightarrow W^+W^-$. This latter reaction will provide a precise measurement of the mass of the W-boson, together with an important test of the electroweak theory via its predictions for the production of longitudinal $W^\pm$. The program of research with LEP II will take at least three years, so that the OPAL research program at LEP will continue to yield exciting physics well towards the end of the decade.

The personnel involved in the OPAL experiment besides those listed as co-investigators include Dr. D. Fong, computer expert at College Park and research associates, Drs. Al Lee, IV, Wayne Springer and Maurice Foucher. (Dr. Lee will leave the group in the Fall of 1992 to become an Assistant Professor at Duke University.) In addition graduate students John Lorah, Han Deng, Robert Lahmann and Gordon Long are working on OPAL. Two graduate students have already received their Ph.D. degrees in 1992. Associate Research Scientist, Richard Kellogg, has assumed major responsibilities for the construction of a new small angle silicon-tungsten luminosity monitor with the assistance of our new research associate M. Foucher. Dr. Wayne Springer has taken over some of Dr. Austin Ball's responsibilities for the hadron calorimeter as Dr. Ball shifts part of his efforts to the SDC detector for SSC. Dr. Lee, IV, will continue with his outstanding software and analysis contributions to OPAL until his departure.

We are also ably assisted by our engineers Rob Bard and John Colmer and physics technician Wyatt Miller at College Park. Physics technician Paul Goldey at CERN has been playing a very important role in the construction of the vertex silicon detectors for OPAL as well as in keeping the OPAL hadron calorimeter in good working order.

In the following sections we shall spell out in more detail some of the physics results obtained by OPAL (Sect. III), descriptions of the performance and future needs of the luminosity monitor (Sect. IV) and the hadron calorimeter (Sect. V) and of the performance and future upgrades of the UMDHEP computer system (Sect. VI).

II. The OPAL Detector

The OPAL Collaboration is the smallest of the four collaborations at LEP. It consists of about 300 physicists from twenty-eight institutions in nine countries on three continents. In 1989 and 1990 OPAL had recorded about 166,000 hadronic decays and 18,000 decays into electrons, muons and taus at center of mass energies near the mass of the Z^0 . In 1991 OPAL has recorded another 352,000 Z^0 decays, the highest number for any of the four LEP detectors. The goal to reach 500,000 Z^0 's by the end of 1991 was accomplished.

The OPAL detector is a general purpose detector, conservative in design, but with the capability to observe completely the wide range of physics accessible with LEP. It consists of the usual components: a series of tracking chambers in a solenoidal field; barrel and endcap

electromagnetic calorimeters; time of flight counters and electromagnetic presampler chamber system; barrel, endcap and "endplug" hadron calorimeters; and a barrel and endcap muon detector. It has an extensive small angle tracking and electromagnetic calorimetry system for luminosity measurement. OPAL has a unique highly distributed data acquisition, triggering and monitoring system based on some 60 Motorola 608020 microprocessors as well as the usual central DAQ computer. Data Analysis follows the usual route of event reconstruction and comparison with fake events generated by Monte Carlo techniques. Many innovative features in our analysis chain have been introduced by OPAL members.

A perspective drawing of the OPAL detector is shown in Figure 1.

The measurement of the trajectories and momenta of charged particles were performed with a precision vertex chamber, a jet chamber and z-chambers. The vertex chamber is divided into 36 sectors with 12 axial and 6 stereo wires each. The jet chamber is a large volume drift chamber divided into 24 azimuthal sectors, each sense wire plane having 159 wires. Each of the wires provided true three-dimensional coordinates, from the wire position and from a drift-time measurement in the $r - \phi$ plane and from a charge-division measurement in the z direction. (The OPAL coordinate system is defined so that the z axis follows the electron beam direction, r is in the plane perpendicular to the z axis and θ and ϕ are the polar and azimuthal angles with respect to the z axis.) In the barrel region, the jet chamber is surrounded by a set of z -chambers, designed to provide an accurate z coordinate measurement where the tracks leave the jet chamber. The chambers are positioned inside a pressure vessel, surrounded by a solenoidal coil which provides a magnetic field of 0.435 Tesla. The pressure vessel and the coil have an effective thickness of about $2 X_0 / \sin \theta$ in the region $|\cos \theta| < 0.7$, where X_0 is one radiation length.

The OPAL silicon micro-vertex detector was installed in March 1991 and entered the data stream in June 1991. It consists of two single sided layers measuring (r, ϕ) coordinates. Each layer is $300 \mu m$ thick with a $25 \mu m$ pitch. There are 25 ladder assemblies with three daisy chained silicon wafers per ladder (3×6 cm). These have new field effect transistor biased wafers (fox fet) with a new readout chip (128 channels). The signal to noise ratio achieved for minimum ionization particles was $\geq 22/1$. The acceptance region is $|\cos \theta| \leq 0.75$, and the single hit efficiency is $\geq 97\%$. Good alignment and excellent performance was achieved with an intrinsic precision of $5 \mu m$.

A sketch of the OPAL Silicon Micro-Vertex Detector is shown in figure 2.

The coil is in turn surrounded by a barrel time-of-flight counter array consisting of 160 scintillator bars with photo-tube readout at both ends. A lead glass electromagnetic calorimeter with a presampler, corresponding to 24.6 radiation lengths and about two hadronic interaction lengths, measures the positions and energies of showering particles. The magnet return yoke serves as a hadron calorimeter and is instrumented with 9 layers of streamer tubes, read out via charge induction onto pads and onto 4 mm wide aluminum strips. The hadron calorimeter also aids in muon identification. The detector is surrounded by four layers of drift chambers for the detection of muons emerging from

the hadron calorimeter. At both ends, end cap detectors provide similar calorimetry over nearly the full remaining solid angle. Four layers of muon chambers, consisting of streamer tubes, give good solid angle coverage of the end caps.

The luminosity of the colliding beams is determined by the observation of small-angle Bhabha scattering events using two identical forward detectors mounted at each side of the interaction point, close to the beam line [107]. Their acceptance covers angles from 40 to 150 mrad in polar angle and 2π in azimuth. A new smaller angle silicon-tungsten luminosity monitors being built to go in front of the existing luminosity monitor. It is described in Section IV.

The momentum resolution of the tracking detectors is $\Delta p/p \approx 8\%$, for $p \approx 45\text{GeV}$. The $\frac{dE}{dx}$ resolution in the central detector for minimum ionizing particles is 3.8%. The electromagnetic energy resolution is typically $\Delta E/E \approx 3\%$ for $E \approx 45\text{GeV}$, except in the region $0.73 < |\cos \theta| < 0.83$, where additional material in front of the calorimeter degraded the energy resolution. The muon chambers provide a precise coordinate measurement for muons, which is used to define the acceptance with a resolution of better than 1 mrad.

The primary event selection was performed by the trigger system [131], which initiated the readout of data from the detector if sufficient activity occurred. The vertex chamber and the jet chamber, which together formed the "track trigger", the time-of-flight detector, the electromagnetic barrel and endcap calorimeters and the barrel and endcap muon chambers each provided independent trigger signals.

The OPAL off-line analysis follows the usual chain of reconstruction and analysis of experimental data and, in parallel, its simulation by Monte Carlo techniques. The OPAL event reconstruction program ROPE (Reconstruction of OPAL Events) addresses both the experimental data as well as simulated events. The event simulation is carried out via GOPAL - the CERN GEANT3 Monte Carlo package particularized to the OPAL geometry and efficiencies. The complexity of the OPAL detector and its analysis requires in addition a data base management system that allows a complete overview of data and detector quality, as well as of the data analysis flow as a function of time. A complete chronological set of calibration constants for the detector is being maintained. In the last two years code to allow easy data streaming for different analysis projects has been introduced. In 1991, a new data analysis system, SHIFT, was successfully introduced. It can handle 3×10^6 events per day.

III. Physics with OPAL

Using the data collected in 1989, 1990 and 1991 OPAL has published or submitted for publication 55 articles in refereed journals through February 1992.

The Maryland group has been involved in many aspects of b decays, in the precise measurement of the Z^0 mass and lineshape, in the search for new types of particles and

Figure 1: The OPAL Detector

Figure 2: The OPAL Silicon Micro Vertex Detector

to a limited extent in aspects of τ decays. The hadron calorimeter has been useful in improving the OPAL lower mass limit for scalar Higgs particles and in improving OPAL's muon detection capabilities. John Lora's thesis is on the measurement of the forward-backward asymmetry of $Z^0 \rightarrow b\bar{b}$ decays and Han Deng is working on the properties of Λ_b particles in a group led by Dr. Lee, IV.

We describe some of OPAL analysis highlights from 1990 and 1991.

III.a. Z^0 lineshape

The measurement of the Z^0 lineshape parameters continues to be an important aspect of the analysis of the data collected with the OPAL detector. Using the full data samples of 1990 and 1991 improved measurements have been made of the Z^0 mass and width, its partial width into hadrons and leptons, and the forward-backward asymmetry of the charged leptons. These results are then combined with the measurement of the τ -lepton polarization and forward-backward polarization asymmetry to determine the effective vector and axial-vector couplings of the charged leptons. From a combined fit of these results to the predictions of the standard model with one loop corrections we extract limits on the mass of the top quark, and the value of the strong coupling constant α_s .

Figures 3 and 4 show the measured cross-sections and forward-backward asymmetries as a function of center of mass energy. The superimposed curves represent the results of a model independent fit to the data. The fit yields the Z^0 mass and width as well as its partial widths to leptons and hadrons,

$$\begin{aligned} M_Z &= 91.161 \pm 0.006 \pm 0.12 \text{ GeV}, \\ \Gamma_Z &= 2.492 \pm 0.011 \text{ GeV}, \\ \Gamma_{ee} &= 82.7 \pm 0.7 \text{ MeV}, \\ \Gamma_{\mu\mu} &= 84.6 \pm 1.1 \text{ MeV}, \\ \Gamma_{\tau\tau} &= 82.6 \pm 1.5 \text{ MeV}, \\ \Gamma_{had} &= 1742 \pm 17 \text{ MeV}. \end{aligned}$$

From the measured cross-sections for leptons and hadrons we obtain for the ratio of the Z^0 partial widths to hadrons and charged leptons, $R = \Gamma_{had}/\Gamma_{ll}$,

$$R = 20.83 \pm 0.17.$$

By comparing the measured value of R with predictions of the standard model including QCD corrections we extract the value of the strong coupling constant α_s ,

$$\alpha_s(M_Z^2) = 0.131 \pm 0.025,$$

for $M_t = 120$ GeV and $M_H = 300$ GeV.

For the partial decay width of the Z^0 into invisible channels Γ_{inv} we obtain,

$$\Gamma_{inv} = 510 \pm 12 \text{ MeV.}$$

Combining the measured value of Γ_{inv}/Γ_H with the SM predictions for Γ_ν/Γ_H we obtain for the number of light neutrinos,

$$N_\nu = 3.08 \pm 0.08(exp.) \pm 0.004(th.).$$

Our measurements of lepton cross sections and asymmetries allow a determination of the magnitude of the vector and axial vector couplings of the charged leptons. Combining these results with measurements of the τ lepton polarization and the forward-backward asymmetry of polarization allows to determine the relative sign of the axial-vector and vector couplings. For the determination of the τ lepton polarization we considered the decay modes, $\tau \rightarrow e\nu\nu$, $\tau \rightarrow \mu\nu\nu$, $\tau \rightarrow \pi\nu$. The polarization of the τ lepton is determined from the shape of the momentum spectrum of the charged lepton or pion in the final state. Our combined results from the three modes for τ polarization and its forward-backward asymmetry are,

$$\begin{aligned} A^{pol}(\tau) &= -0.03 \pm 0.08, \\ A_{FB}^{pol}(\tau) &= -0.20 \pm 0.08. \end{aligned}$$

The values of the charged lepton couplings from the fits to the lepton cross sections, forward-backward asymmetries and the tau lepton polarization measurements are,

$$\begin{aligned} g_e^a &= -0.4979 \pm 0.0023, \\ g_\mu^a &= -0.5044 \pm 0.0033, \\ g_\tau^a &= -0.4976 \pm 0.0045, \\ g_e^v &= -0.035 \pm 0.0011, \\ g_\mu^v &= -0.007 \pm 0.019, \\ g_\tau^v &= -0.027 \pm 0.014. \end{aligned}$$

Since our data is in agreement with the predictions of the standard model, we use them to constrain the mass of the top quark. The program ZFITTER is used to obtain full one-loop standard model predictions. The input parameters for the calculations are α , α_s , G_F , M_Z , M_t , and the Higgs mass M_H . Several configurations of the OPAL data have been

fit to the SM prediction. In one fit we combined the OPAL data with the measurement of the W mass from pp collisions and the determination of the $\sin^2 \theta_W$ in neutrino nucleon scattering and constrained the value of α_s using the OPAL measurement from a study of jet rates. Figure 5 shows the χ^2 of the fit as a function of the top quark mass. From this analysis we obtain an estimate for the top quark mass,

$$M_t = 134^{+28}_{-31} \pm 20 \text{ GeV}.$$

The second error shows the variation for the Higgs mass spanning the range from 50 to 1000 GeV.

III.b. Heavy Flavor Physics with OPAL

With the increased statistics of the LEP data the study of heavy flavor production has become a major thrust of the OPAL physics analysis. Using the 1990 data we obtained the following results on the production and decay properties of b and c hadrons:

1. Measurement of the couplings for $Z^0 \rightarrow b\bar{b}$ and $Z^0 \rightarrow c\bar{c}$, using muon inclusive hadronic Z^0 decays.
2. Measurement of $B^0 - \bar{B}^0$ mixing.
3. Observation of J/ψ production in Multihadronic Z^0 Decays.
4. Measurement of the Average B hadron lifetime using Inclusive Leptons.
5. Measurement of D^{*+} production in Z^0 Decays.

These results have been published in [121], [145], [133], [144], and [123] and have been described in brief in our previous progress reports.

While we have thus far established that the Z^0 couplings to the b and c quarks are consistent with the standard model, the present accuracy of the measurements is far from being able to test the detailed intricacies of the standard model. Most of the measurements described above can benefit from an increase in the statistics. We are currently in the process of analysing the 1991 data for improvements in the above measurements as well as new measurements including searches for the Λ_b baryons and the B_c meson and exclusive reconstruction of B meson final states. The latter could lead to a direct measurement of the ratio of the lifetimes of the neutral and charged B mesons.

OPAL

Figure 3: (a) Energy dependence of cross-section for $Z^0 \rightarrow \text{hadrons}$ (b) Energy dependence of cross-section for $Z^0 \rightarrow \text{leptons}$

OPAL

Figure 4: Lepton forward-backward asymmetry

Figure 5: The χ^2 curves resulting from combining the full set of OPAL's cross sections and forward backward asymmetry measurements with the ratio M_W/M_Z from UA2, M_W from CDF and $\sin^2 \Theta_W$ from the νN scattering experiments CDHS and CHARM

Recently from the 1990 and 1991 data we extracted evidence for the production of the Λ_b baryon. In the following we will give a brief description of this result, a recent measurement of the $\Gamma_{b\bar{b}}$ using electron inclusive hadronic Z^0 decays and a measurement of average B hadron lifetime with 1990 data.

Evidence for b-flavored Baryon Production in Z^0 Decays at LEP [152]

Semileptonic decays of b baryons are expected to produce $\Lambda\ell^-$ and $\bar{\Lambda}\ell^+$ pairs but not $\Lambda\ell^+$ and $\bar{\Lambda}\ell^-$ pairs, where ℓ is an electron or a muon. Most other sources of leptons and Λ 's do not have such a correlation. Furthermore the kinematic features of the ℓ and Λ pairs from b-baryons provide additional discrimination against background sources. Due to the large mass of the b quark, leptons resulting from semileptonic b hadron decays tend to have large momentum and high transverse momentum relative to the b hadron direction. In analogy to $\Lambda_c \rightarrow \Lambda X$ decays, the Λ_b is expected to decay predominantly into Λ_c , followed by the Λ_c decay into a Λ baryon. As a result a large fraction of Λ_b decays will produce a Λ ; similar decay chains are expected for other b baryons. Monte Carlo studies have shown that the final state Λ baryons retain a large fraction of the momenta of the Λ_b . The fragmentation processes and B meson decays produce Λ at much lower momentum and transverse momentum.

Using the 1990 and 1991 data samples we have observed evidence for the production of b-flavoured baryons by detecting an excess in the production of $\Lambda\ell^-$ and $\bar{\Lambda}\ell^+$ pairs in hadronic Z^0 decays. Figure 6(a) shows the invariant mass distribution of Λ candidates for $\Lambda\ell^-$ pairs (charge conjugate implied). We find a total of 68 events at the mass of Λ baryon. The invariant mass distribution of Λ candidates for the wrong sign pairs ($\Lambda\ell^+$) is shown in figure 6(b), giving 13 events at the mass of Λ . Using Monte Carlo studies we estimate the number of expected events from various processes other than b-baryon decays to be 3.1 $\Lambda\ell^-$ events and 0.3 $\Lambda\ell^+$ events. The wrong sign pairs provide an estimate of the random combinatorial background.

After subtracting the wrong sign background we find $55 \pm 9 \pm_{3.1}^{+0.3}$ events, which we interpret as originating from semileptonic decays of b-flavoured baryons. Assuming that the weakly decaying b baryons produced in Z^0 decays are mostly Λ_b particles, we estimate the product branching ratio $\Gamma_{b\bar{b}}/\Gamma_{had} \times f(b \rightarrow \Lambda_b) \times B(\Lambda_b \rightarrow \Lambda\ell\nu X)$, averaged over electron and muon channels, to be $(6.2 \pm 1.0 \pm 1.5) \times 10^{-4}$.

A Measurement of the $Z^0 \rightarrow b\bar{b}$ using electron inclusive hadronic Z^0 decays

In reference [121] we have described our measurement of $\Gamma(Z^0 \rightarrow b\bar{b})$ and its forward-backward asymmetry using muon inclusive hadronic Z^0 decays. Recently we have also measured $\Gamma(Z^0 \rightarrow b\bar{b})$ using electron inclusive hadronic Z^0 decays [x6].

The electron selection in OPAL is based on the ionization loss measured in the jet chamber, the amplitude of the barrel presampler cluster associated to the central detector track, the lateral distribution of energy in the barrel lead-glass cluster associated to the track and

the comparison of the track momentum with the lead-glass cluster energy. For example figure 7 shows the distribution of $N_{dE/dx}^{\sigma} = (dE/dx(\text{measured}) - dE/dx(e))/\sigma_{dE/dx}$, for a set of electron candidates passing all cuts but before applying the cuts on dE/dx measurements. The peak at around zero is due to true electron tracks with a measured dE/dx consistent with the expected value for electron. Similarly in figure 8 we show the distribution of the ratio of the lead-glass energy cluster to the track momentum for the electron candidates passing all cuts but before applying the requirements on the lead-glass energy. Using the 1990 data we have measured the production rate of electrons with momentum $p > 4$ GeV and large transverse momentum with respect to the jet containing the electron. The dominant source of electrons in this kinematic range is semileptonic decays of b hadrons. Accounting for the various background sources and assuming that the average semileptonic decays of the b hadrons at LEP energies is the same as at the $\Upsilon(4S)$, we determine the $\Gamma_{b\bar{b}} = 394 \pm 13 \pm 32$ MeV.

Measurement of the Average b lifetime using Inclusive Leptons

Using the sample of events containing lepton candidates the average lifetime of B hadrons was measured from the distribution of the impact parameter of lepton candidates. In figure 9, we show the impact parameter distribution of electron and muon candidates, with $p > 4.5$ GeV/c, and $p_T > 1.5$ GeV/c and $|\cos(\theta)| < 0.7$. The kinematic cuts were applied to suppress leptons not originating from semileptonic B decays. The cut on the polar angle ensures that the tracks are in the fiducial volume of the Z chambers. In addition, tracks are required to have at least 6 axial vertex chamber hits (from a maximum of 12). In order to extract the b lifetime a maximum likelihood fit was performed to the impact parameter distribution. The likelihood function contained the expected impact parameter distributions for leptons originating from various sources contributing to the inclusive lepton sample. This analysis yields, an average lifetime for B hadrons weighted by the semileptonic branching fractions and production rates of B hadrons at the Z^0 pole, of $\tau_b = 1.37 \pm 0.07 \pm 0.06$ ps, where the first error is statistical and the second is systematic. This measurement which is the most precise measurement of the b lifetime is consistent with previous measurements at PEP and PETRA and with other measurements at LEP.

III.c. Update of OPAL Search for Higgs Scalar Particles [137]

Since our last report, OPAL has published

1. A Decay Mode Independent Search for (Light) Higgs.
2. An Improved lower limit for the Standard Model Higgs.
3. More accurate limits on Minimal Supersymmetric Model Higgs Scalars, h_0 and A_0 .

Figure 6: (a) The $p\pi$ invariant mass distribution of the Λ particles for Λe^- candidates (hatched Histogram) and the $\Lambda \mu^-$ candidates (open histogram); (b) The $p\pi$ invariant mass distribution of the Λ particles for Λe^+ candidates (hatched Histogram) and the $\Lambda \mu^+$ candidates (open histogram).

Figure 7: $N^\sigma_{dE/dx}$ with $p > 4$ GeV/c in hadronic events after other electron selection criteria have been applied

Figure 8: The fits to the E/p distributions in three momentum bins. The points are electron candidates passing all electron selection criteria but the E/p requirement. The hatched histograms show the background component determined from data

Figure 9: Impact parameter distributions of electrons and muons

IIIc.1. Decay Mode Independent Search for a Higgs Scalar

In this work one searches for events of types given by the figure below:

The topologies are

- i. inclusive acollinear lepton pairs or
- ii. large isolated EM energy plus a few charged tracks.

Using the 1990 data (6.8 pb^{-1}) and half of the 1991 data (5.6 pb^{-1}) one finds an H^0 mass limit of $13.3 \text{ GeV}/c^2$ (95% c.l.). The same search rules out a light scalar, S^0 , below a mass of $11.1 \text{ GeV}/c^2$ if its coupling is the same as the H^0 .

III.c.2. Improved Lower Limit for the Standard Model Higgs

Using the methods described in last year's Progress Report, upgraded to include the full 1991 data sample OPAL was able to push the lower limit for the mass of the Standard Model Higgs particle to $51 \text{ GeV}/c^2$ at 95% confidence level. This lower limit will rise slowly until LEP II data becomes available, when the mass region up to $80\text{-}90 \text{ GeV}/c^2$ will become available to experiment.

III.c.3. Search for Minimal Supersymmetric Model Higgs

In this model there are at least two complex Higgs fields, since the up and down quarks are coupled to different fields to attain their masses. One introduces a parameter β , such that $\tan\beta = v_2/v_1$ where v_2 and v_1 are the vacuum expectation values for the Higgs fields coupled to u and d respectively. This minimal SUSY model contains 5 physical Higgs bosons: 2 with $\text{CP} = +1$ called h^0, H^0 ; 1 with $\text{CP} = -1$ called A^0 ; and 2 singly charged scalars, H^+, H^- . h^0 and A^0 are the lightest neutral bosons. If $\tan\beta > 1$, $h^0, A^0 \rightarrow b\bar{b} \approx 93\%$ of the time, $\rightarrow \tau^+\tau^- \approx 5\%$. Whereas if $\tan\beta < 1$, $h^0, A^0 \rightarrow c\bar{c} \geq 99\%$. Searches have been carried out for $Z^0 \rightarrow h^0 + A^0$ where $h^0, A^0 \rightarrow jj$ or $\tau^+\tau^-$ and for $Z^0 \rightarrow Z^{0*} + h^0$, where

$Z^0 \rightarrow \ell^+ \ell^-$ or $\nu n \bar{u}$: If one assumes $m_{h_0} = m_{A^0}$; one obtains a limit $m_{h_0} \geq 43 \text{ GeV}/c^2$. figure 10 shows the complicated boundaries in m_{h_0}, m_{A^0} excluded by OPAL searches using 12.4 pb^{-1} of data from 1990 + 1991. Elaborate analyses have been carried out on the implication of the negative searches including the radiative one loop corrections which have recently been shown to be important.

III.d Search for Massive Unstable Photinos that Violate R Parity

The apparent anticorrelation of the solar-neutrino signal with the 11 year sunspot cycle observed by Davis [1] can be explained if the electron neutrino has a large magnetic moment. K.S. Babu and R.N. Mohapatra [2] have shown how this might be achieved within the framework of an unusual, but relatively simple, supersymmetric extension of the standard model with R parity violating interactions. In this model the neutrinos have a large transition magnetic moment such that a ν_e can transform into a "sterile" ν_μ in the sun's magnetic field. A discrete symmetry between e and μ lepton families is introduced. Individual lepton number conservation does not hold but the combination $(L_e - L_\mu)$ remains a good quantum number. The presence of $(L_e - L_\mu)$ symmetry forbids rare processes such as $\mu \rightarrow e\gamma$, $\mu \rightarrow 3e$ as well as neutrinoless double beta decay. Unlike usual supersymmetric extensions of the standard model, in this model the mass of the selectron, $\tilde{e}$, the spin 0 supersymmetry partner of an ordinary electron, is restricted to lie in the mass range below $\approx 100 \text{ GeV}/c^2$, if a sufficiently large neutrino magnetic moment ($\approx 10^{-10} \mu_B$, where μ_B is the proton Bohr magneton) is to be achieved. Direct searches [3] for the selectron at LEP and SLC have shown that its mass must be greater than $\approx 43 \text{ GeV}/c^2$. At Maryland, we have carried out an indirect search for the reaction

$$e^+ e^- \rightarrow \tilde{\gamma} \tilde{\gamma} \quad (1)$$

where $\tilde{\gamma}$ designates the lightest supersymmetric particle assumed here to be a pure photino. Thus the decay $Z^0 \rightarrow \tilde{\gamma} \tilde{\gamma}$ is strictly forbidden due to the vanishing coupling of Z^0 to a pair of photinos. This reaction proceeds by the exchange of a selectron (see figure 11(a)), and has a cross section which depends on $M_{\tilde{e}}$, the selectron mass. Following [2] we assume that the photino decays into the following decay modes which violate R parity and L_τ but not $(L_e - L_\mu)$ (See figure 11(b)):

$$\tilde{\gamma} \rightarrow \tau^+ e^- \nu_\mu. \quad (2a)$$

$$\rightarrow \tau^- e^+ \bar{\nu}_\mu. \quad (2b)$$

$$\rightarrow \tau^+ \mu^- \nu_e. \quad (2c)$$

$$\rightarrow \tau^- \mu^+ \bar{\nu}_e. \quad (2d)$$

OPAL

Figure 10: Mass limit on h^0 and A bosons

Since events from reaction (1) followed by the decay (2) would have quite spectacular signatures, it is possible to search for such events in the presence of hundreds of thousands of Z^0 events. The strategy of this search is to look for events with track multiplicity ≤ 20 that contain at least two high momentum leptons, one in each hemisphere of the event defined by the thrust axis. Charged tracks of "good" qualities are selected according to standard OPAL criteria. The number of "good" tracks is required to be between 4 and 8. A typical $\tilde{\gamma}\tilde{\gamma}$ event will contain two or four charged tracks in each hemisphere. We demand that in at least one hemisphere there be exactly 2 or 4 tracks. Dominant backgrounds from $Z^0 \rightarrow \tau^+\tau^-$ and $e^+e^- \rightarrow l^+l^-l'^+l'^-$ are removed by appropriate visible invariant mass cuts in each hemisphere and the $\Sigma |\vec{p}|/\sqrt{s} \leq 0.9$ cuts respectively.

The complete samples of OPAL data from 1990 and 1991 corresponding to an integrated luminosity of 21pb^{-1} in the Z^0 energy region were examined and no event satisfied all requirements.

This negative experimental result has been transformed into a lower limit for $M_{\tilde{e}}$ as a function of $M_{\tilde{\gamma}}$ within the framework of the Babu-Mohapatra model. Using the production and decay distributions previously discussed, we have carried out a Monte Carlo simulation for a grid of values of $M_{\tilde{e}}$ and $M_{\tilde{\gamma}}$, using the appropriate programs [4] to describe the response of the OPAL detector. We thus obtain the number of events expected in our sample that would satisfy the selection criteria. Table I shows the number of events expected for various photino and selectron masses. Since no events were observed, we set the 95% CL limit at those points of the $(M_{\tilde{e}}, M_{\tilde{\gamma}})$ plane where the number of expected events equals 3. Table II shows the results.

In figure 12, the 95% CL exclusion from this experiment is displayed as a function of $M_{\tilde{\gamma}}$ and $M_{\tilde{e}}$ for the region $M_{\tilde{\gamma}} \geq 5\text{GeV}/c^2$, $M_{\tilde{e}} \geq 43\text{GeV}/c^2$. If the $\tilde{e}$ has a mass below $43\text{GeV}/c^2$, it can be copiously pair produced in Z^0 decays. Previous searches for such particles by LEP experiments [3] gave negative results. Although the region $M_{\tilde{e}} \leq 43\text{GeV}/c^2$ is not displayed in figure 12, our negative search gives no indication of $\tilde{\gamma}$ production via such low mass $\tilde{e}$ exchanges. Our present search complements previous LEP searches and excludes a large domain in the $(M_{\tilde{e}}, M_{\tilde{\gamma}})$ plane allowed by the model of Babu and Mohapatra. On the other hand, if χ^0 , the lightest spin 1/2 supersymmetric particle called the neutralino, is not a pure photino but has an important zino or higgsino component, our conclusion can be weakened, unless the dominant χ^0 decays remain those listed in (2). In the latter case, a new source of events could be produced via the supersymmetric processes $Z^0 \rightarrow \chi^0\chi^0, \chi^0\chi'^0$, followed by χ^0 decaying via their $\tilde{\gamma}$ component into the final states listed in (2). Such events would constitute an important background to the Babu-Mohapatra process. However since we do not see any such events, these additional potential reactions do not affect our limits on $M_{\tilde{e}}$ via the alternative $\tilde{e}$ exchange process for photino pair production shown in figure 11(a).

In conclusion, a search has been carried out for unstable photinos that decay into leptons according to a theory conjectured by Babu and Mohapatra in which neutrinos have a large transition magnetic moment. No evidence for such esoteric objects has been seen. A large fraction of the range of selectron masses allowed by the Babu-Mohapatra model is ruled out by this search. This result will soon be submitted to Physics Letters B for publication.

Table I Number of events expected for $e^+e^- \rightarrow \tilde{\gamma}\tilde{\gamma}$ according to the Babu-Mohapatra model.

Masses (GeV/c ²)	Expected Number of Events		
	$M_{\tilde{e}} = 40$	$M_{\tilde{e}} = 70$	$M_{\tilde{e}} = 100$
$M_{\tilde{\gamma}} = 10$	35	17	7
$M_{\tilde{\gamma}} = 20$	33	13	6
$M_{\tilde{\gamma}} = 30$	16	6	3
$M_{\tilde{\gamma}} = 40$	4	2	1

Table II 95% CL lower limit for $M_{\tilde{e}}$ as a function of $M_{\tilde{\gamma}}$ in units of GeV/c².

	$M_{\tilde{\gamma}} = 10$	$M_{\tilde{\gamma}} = 20$	$M_{\tilde{\gamma}} = 30$	$M_{\tilde{\gamma}} = 40$
$M_{\tilde{e}}$ -Lower limit	135	122	95	51

References

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III.e Quantum Chromodynamics at LEP

As described in earlier progress reports OPAL has shown that QCD works extremely well in describing the characteristics of the hadronic events found in Z^0 decays. The vector and non-abelian nature of the gluon and the falling of the strong coupling constant α_s with

Figure 11: (a) Feynman diagrams for photino production in e^+e^- annihilations by the Babu-Mohapatra mechanism ; (b) Feynman diagrams for the decays of the photinos via intermediate massive scalar particles

Figure 12: 95% CL exclusion contour in the $(M_{\tilde{\gamma}}$ and $M_{\tilde{e}}$) plane deduced from this search. The region allowed by the Babu-Mohapatra model is indicated

energy (asymptotic freedom) have been established. A summary of this work along with the similar work from other LEP detectors has recently been submitted by S. Bethke and S. J. Pilcher to Annual Review of Nuclear and Particle Science, Vol. 42 (1992) in an article entitled "Tests of Perturbative QCD at LEP".

OPAL has recently completed a global determination of $\alpha_s(M_{Z^0})$ at LEP (159). The value of the strong coupling constant $\alpha_s(M_{Z^0})$ is determined from a study of 15 different observables in hadronic Z^0 and τ decays. 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. 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

$$\alpha_s(M_{Z^0}) = 0.122^{+0.006}_{-0.005} \text{ in } O(\alpha_s)^2.$$

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 the result with a reduced sensitivity to renormalization scale variations.

Two completely independent methods of determining α_s exist from measurements of the ratios of hadronic to leptonic decay widths of the Z^0 and the τ -lepton. For the Z^0 , the ratio $R_Z = \Gamma_{had}/\Gamma_{e\mu\tau}$ predicted by the electroweak Standard Model is modified by a factor

$$\Gamma_{QCD} = 1 + (\alpha_s/\pi) + 1.41 (\alpha_s/\pi)^2 - 12.8 (\alpha_s/\pi)^3$$

Using the OPAL measurement $R_Z = 20.98 \pm 0.22$ and adding all other uncertainties in quadrature one obtains to order α_s^3

$$\alpha_s(M_{Z^0}) = 0.148 \pm 0.021.$$

The ratio $R_\tau = B(\tau \rightarrow \text{hadrons} + \nu)/B(\tau \rightarrow e\bar{\nu}_e\nu_\tau)$ also involves a QCD correction that has recently been calculated to $O(\alpha_s^3)$. OPAL finds $R_\tau = \frac{1-B_e-B_\mu}{B_e} = 3.795 \pm 0.119 \pm 0.111$. This yields for α_s at the mass of the τ :

$$\alpha_s(M_\tau) = 0.389^{+0.073}_{-0.075},$$

where all experimental and theoretical errors have been combined in quadrature. Using QCD to navigate from the mass M_τ to the mass M_{Z^0} crossing the appropriate quark thresholds along the way, one finds

$$\alpha_s(M_{Z^0}) = 0.123^{+0.006}_{-0.007}.$$

Because of the logarithmic behavior of α_s as a function of the scale factor μ , the relative error ($\Delta\alpha_s/\alpha_s$) shrinks when α_s is extrapolated from a low to a higher energy.

The accurate result from τ decay is in remarkably good agreement with the result obtained by studying the hadronic events at the Z^0 . This constitutes an important consistency check of the reliability of perturbative QCD.

IV. The OPAL Luminosity Monitor

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IV.a. The OPAL Small Angle Electromagnetic Calorimeter

The asymptotic approach to the irreducible systematic error in the OPAL luminosity measurement has made 1991 a long hard year for the forward detector group. Performance of the detector itself during the past LEP season was excellent. During the 1990-1991 shutdown, a significant fraction of the dead channels in the tube chamber system were recovered, and the stability of the pedestals was improved. The tube chambers are crucial for determining the absolute luminosity, and the improved detector performance gives us hope that the error in the absolute luminosity can be reduced beyond the 0.7% achieved in 1990. Improving the 1990 analysis is not trivial, however, and the results are not yet in.

The relative luminosity measurement depends only on the calibration stability of the calorimeter and the degree of cleanliness of the LEP beams. Both were excellent in 1991. An automatic calibration algorithm was implemented in the front-end read-out processor which allowed the calorimeter gains to be tracked on a significantly finer time-scale than in previous years. We were therefore able to reduce the systematic error in the fill-to-fill relative luminosity measurement by a factor of 4, from 0.80% to 0.20%. The observed number of hadronic events, it is important to reduce it in step with improvements in the LEP luminosity. The 0.81% in 1990 would have been equivalent to the statistical error inherent in 15k hadronic events per fill. In 1991 the largest fills produced almost 8k hadronic events. The present calibration error of 0.2% is appreciable until LEP is able to produce more than 100k hadronic events per fill.

The improvements in the calorimeter trigger system necessary to monitor accidental

backgrounds when LEP upgrades to 8 on 8 bunches have been postponed until they can be integrated with the trigger system for the new Si-W luminometer.

IV.b. The new Silicon-Tungsten Luminometer

Progress on the OPAL Silicon-Tungsten Luminometer remains on course for its planned completion a year from now, in time for the 1993 Lep season. The goal of this detector, which was approved by the LEPC last November, is to measure the absolute luminosity of the colliding beams with a systematic error of one part per thousand. Such accuracy in the luminosity will match the statistical uncertainties inherent in the sample of several million Z^0 events which Lep is expected to produce before the commencement of the Lep II program. Among the more crucial aspects of Z^0 line shape physics for which the new luminometer will make dramatic improvements is determining of the ratio of the invisible to the leptonic width of the Z^0 . This quantity is precisely and unambiguously predicted by the Standard Model in a manner free of QCD corrections, and therefore provides a direct, high-precision test of the Electro-weak couplings.

An important consideration for the Si-W Luminometer project is its time-scale. Unless the detector is installed in March 1993, in time for next year's Lep season, the probability of obtaining a statistical sample of Z^0 decays worthy of the new detector's precision is significantly reduced. The energy of Lep is currently scheduled to be upgraded beyond the WW threshold in 1994. Although the installation and commissioning of the requisite number of super-conducting RF cavities may be postponed somewhat beyond this date, Lep running on the Z^0 resonance will not continue forever.

The compressed schedule for construction of the Si-W calorimeter is radical for such a state-of-the-art detector. Since a part-per-thousand luminosity measurement requires a systematic uncertainty of 18 microns in the absolute determination of the inner acceptance radius, as well as 2% energy resolution to separate the Bhabha scattering signal from accidental backgrounds, we have settled on a design incorporating 576 Silicon wafers to sample the electromagnetic showers generated in a stack of Tungsten plates by small-angle Bhabha electrons. Each wafer is divided into 64 2.5 mm-wide silicon pads, each of which is read out individually. The electronic gain of each of the 36,000 charge-sensitive read-out channels must be known to 1%. A fundamental consideration in designing a detector of such performance on a tight time-scale, was the use of only proven state-of-the-art technology. We were encouraged to attempt the project only because a CERN-SACLAY team working for the ALEPH collaboration had recently succeeded in developing an application-specific integrated circuit called the AMPLEX-SICAL which was suited to our needs. The other critical aspect of the project, the silicon detectors themselves, are standard technology, but the quantity necessary for the OPAL project does represent a significant fraction of the production capacity of most manufacturers over the time available.

The Maryland group carries primary responsibility for characterizing the performance of the front-end electronics, for assuring the quality of the completed detector modules, and

for providing the Silicon detectors themselves.

The initial project milestones were to acquire familiarity with the AMPLEX-SICAL chip, to fix the design of the silicon detectors themselves, acquire prototypes from industry, and place orders for their production as soon as possible. We have now succeeded in all these aspects, and are moving toward the real job of actually putting the detector together.

One of our primary concerns with the AMPLEX-SICAL chip was the fact it was not "certified", ie., no manufacturer would assume the risk of guaranteeing production of functional chips. Although the ALEPH production run had proved that the basic design of the chip was satisfactory, the protection of the inputs against damage through electrostatic discharge was considered inadequate. After consultation with IMEC, the manufacturer of the chip, we undertook an improvement in the input protection circuitry which may allow the design to be certified. Our production run of 6700 chips, completed in February, was, however, undertaken entirely at our risk. Fortunately it has been a success. We have tested two wafers of the 22 produced, and the yield appears to be about 60%, significantly better than the 42% observed in the ALEPH production. We are currently completing construction of an automated probe station which will allow efficient characterization of our chips before they are mounted on the ceramic boards of our detector. A sophisticated data acquisition system which allows systematic variation of the AMPLEX operating parameters has already been completed. Figure 13 shows the variation in crosstalk observed on each of the sixteen channels of a single AMPLEX chip, and is illustrative of the detail with which we characterize the behavior of every chip to be used in the detector.

Two manufacturers (Micron and Hamamatsu) have already provided satisfactory prototype detectors which meet our specifications. Tests of these prototypes are still in progress, and we will place our order for the series production by the end of April, just two weeks later than we planned in November. Both manufacturers promise to complete delivery of our order by September, or even August, more than six weeks ahead of the schedule in our proposal.

A prototype detector assembly, including a Silicon detector bonded to the hybrid ceramic circuit board which marries the Silicon detector to the AMPLEX chips, and the motherboard printed circuit which completes the front-end electronics of the detector, have all been tested. Layout of the board incorporating the digitization electronics has been completed, and a detailed functional design of the trigger exists.

Extensive work has been completed on a mechanical prototype to verify whether our engineering design can meet the demanding requirements on assembly tolerances. Extensive portions of the final detector support structure are already being fabricated.

The fully machined Tungsten plates are due to be delivered by the end of June. In short, although real production of the detector is just beginning, we have already passed several significant milestones, and the prospects for completing a detector of unprecedented precision, on time, are excellent.

XTLK0010

fig.2B) AVG. XTLK FOR INPUT VS OUTPUT

Figure 13: Variation of cross-talk for an AMPLEX chip

V. The OPAL Hadron Calorimeter

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The OPAL hadron calorimeter (HCAL) continued to operate reliably until the end of the 1991 LEP run, and following the winter shutdown, has been successfully recommissioned ready for 1992 running. The principal modification has been the upgrading of the data acquisition system.

V.a. Detector Status

The excellent overall reliability of the HCAL hardware and data acquisition system is reflected in the observation that 98% of the $Z^0 \rightarrow$ multihadron events taken during 1991 have both towers and strips fully operational.

The trend towards increased stability was demonstrated by the absence of any significant hardware failures during the last three months of the 1991 run. Similarly, it has been possible to re-commission in 1992 without any chambers misbehaving under high voltage.

Investigation of two apparently leaking 36 chamber endcap quadrants (1/4 layers) did, however, reveal large leaks in both these adjacent quadrants. Records suggest this damage occurred during early 1991 and suspicion is focussed on a local overpressure excess. All the affected chambers function perfectly, but the CERN bubbler-free gas distribution systems allow common return manifold gas to flow backwards into leaky circuits, presenting a major safety hazard. By a combination of major surgery on the accessible part of both damaged quadrants and return flow restriction in the least leaky quadrant, a safe condition has been reached with only 24 chambers of one quadrant disconnected. Removal, diagnosis and possible replacement of this quadrant will be attempted during the 1992-93 shutdown. Specialist support frames will be necessary.

The calorimetry readout chain, consisting of summing amplifiers, receivers and ADC's, remains extremely reliable, with typically $< 0.5\%$ of the approximately 1000 towers being noisy or inoperative. Most problems are attributable to the charge integrating daughter boards in the 32-channel CIA cards.

Final integration of the hadron trigger into the OPAL 2nd level trigger matrix awaits the resolution of persistent cabling problems with the section serving the pole-tip. All the comparator and matrix mapping modules involved have been confirmed in working order, and most of the interconnect ribbon cables have been replaced. The barrel and endcap sections continue to operate satisfactorily, although it is hoped to reduce the present 1.6 GeV threshold in each 4×4 tower trigger element.

V.b.Recent Upgrades

Significant changes were made to both the data acquisition and the control and monitoring systems of the hadron calorimeter during the Winter 1991-1992 shutdown of LEP. The main objective was to increase the speed and reliability of both systems. The hardware modifications consisted of the addition of a second CPU (Motorola MVME 167) to each VME DAQ crate as well as the installation of a third VME local system crate dedicated to the control and monitoring. A schematic of the final system is shown in Figure 14.

Data Acquisition System

The improvements in the HCAL data acquisition system were made in the context of a general DAQ upgrade. In anticipation of the expected increase in LEP luminosity, a program to reduce the dead-time of OPAL has been undertaken. While typical average dead-times of the subdetectors were under 10 ms in 1991, the overall experiment dead-time had significant tails above 20 ms due to the nature of the front end processors. The data acquisition system consists of 16 subdetectors each using one or more 68020- and 68030-based processors running the OS9 operating system. Until this year, most of these processors ran many tasks in addition to front-end readout. Since OS9 is not a true multitasking system, other processes could interfere with the process performing the read-out. When this interference (known as "time-slicing") occurred, the "dead-time" of that sub-detector was longer for that event. This only happened in about 1/1000 events in a given subdetector. However, since there are 16 subdetectors and the "time-slicing" of the readout processes of different subdetectors is generally not correlated, the overall dead-time had significant "tails".

The "time-slicing" problem for the HCAL Towers has largely been avoided by the introduction of an additional MVME 167 processor in each VME crate. The original processor (CES FIC 8320) now only runs the front-end read out and an additional process to transfer the event from FIC to MVME 167. The MVME 167 processor performs further processing and the transfer of the events to the OPAL Event Builder. The MVME 167 also handles all service and monitoring tasks such as networking, histogramming, etc. Using this dual CPU setup, the hadron towers data acquisition system has been observed to run at rates as high as 100 Hz with a dead-time of 5.2 ms and no "tails". Similar results are confidently expected from the much simpler hadron strips system once manpower can be released to fully implement the necessary changes.

Multibunch Operation

The expected progressive decrease in the time between collisions in LEP poses a severe challenge to a readout system designed around a collision interval of $22\mu s$. Originally, (for 18×18 or more bunches) replacement of the ADC's and the associated receiver and trigger cards was thought to be inevitable.

Figure 14: Schematic of the Upgraded DAQ System for the Hadron Calorimeter

However, we are evaluating a method of reducing the average dead-time of the existing CAMAC-based system. Using the Smart Crate Controller (SCC) system developed at Fermilab, the average contribution to dead-time from the read-out of the charge integrating ADC's (CERN-developed CIA's) should be reduced by a factor of approximately 2.5. The SCC consists of a crate controller which runs the CAMAC bus at a 600 ns cycle time compared with the usual 2 μ s cycle time. This is operated in conjunction with a VME memory buffer which can hold two events. With this system we expect to reduce the dead-time of the tower read-out of the hadron calorimeter to under 2.5 ms, giving (at a fraction of the cost) an increase in performance comparable to that anticipated if the CAMAC based CIAs were replaced by a FASTBUS based system.

The long gate time (2.5 μ s) needed to collect charge from large towers ruled out a hadron component in the first stage of the new, two-stage OPAL trigger developed for LEP running with 8×8 bunches. Logic modifications and additions necessary to introduce an abort and reset in the absence of a first stage trigger have been implemented and tested.

The installation of a third VME crate and separate CAMAC branch to perform the monitoring and control tasks described below should also serve to increase the speed and reliability of the data acquisition system.

Control and Monitoring System

The modified readout configuration, with a dedicated data acquisition processor, allows additional monitoring and control tasks to be performed on the new MVME 167. Detailed information about the high-voltage behavior of the chambers is now being stored on the hard disk of the VME crate. This information is periodically copied to the VAX cluster where a histogramming package produces various history plots. This enhanced monitoring capability will be exploited particularly to pinpoint the few individual chambers whose disconnection will eliminate remaining high voltage instabilities.

In addition to the high voltage monitoring and control, the new VME crate also hosts the recently implemented underground gas gain monitoring system. It is envisaged that a feedback mechanism will be implemented to automatically maintain constant gain in this cosmic ray monitoring station by adjusting anode voltage to compensate for atmospheric pressure variations. Ultimately, this may allow gain stabilization for the whole hadron calorimeter to be automated. During 1992, however, the tedious but reliable manual adjustments, based on surface cosmic ray gain monitor results, will continue. It is also planned to control the Wire Monitor Latch (WML) pulsing and singles-rates system from the new VME crate. The measurement of counting rates from each of the 6- or 7-chamber quarter-layers will confirm that each working chamber of the hadron calorimeter is indeed active.

V.c. Calibration and Simulation

The conversion from tower charge to energy is based on the response to normally incident muons, since the hadronic energy producing the same charge as a muon is known from test beam studies. Corrections are made for any inoperative or under-voltage layers on an event by event basis using a fault data-base and the HV status incorporated in the event record for this purpose. In addition, random triggers are analysed on a run-by-run basis to eliminate noisy towers.

Simulation of the hadron calorimeter relies on the GOPAL program incorporating the shower Monte Carlo GEISHA. This reproduces the overall shape of the energy and strip-hit distributions per layer reasonably well, but small changes in the parameters produce quite large discrepancies in overall scale. To avoid frequent re-tuning, a new simulation philosophy will be evaluated, based on empirical distributions obtained from test beam studies and observations of isolated pions within OPAL. Exact simulation of the hadronic shower mechanism is very unlikely to provide better interpretation of HCAL data than a simple model based on observed energy and hit distributions.

V.d.Applications

The hadron calorimeter continues to play a crucial role in the identification of neutral jets which deposit little or no energy in the electromagnetic calorimeter. These are an important background to the neutral energy signature of a standard model Higgs boson, for which the OPAL lower mass limit now stands at $51 \text{ GeV}/c^2$. Mainly neutral jets can also fake the low charged multiplicity of a τ decay, giving the HCAL an important role in rejecting background to the τ lepton sample.

In muon identification, the HCAL strips continue to play an important role in complementing the barrel and endcap muon chambers. An independent muon finder, using only central detector and HCAL information, has recently been developed. The efficiency is 68% for muons from μ -pair events and 50% for muons in simulated multihadronic events, where $\sim 70\%$ of the candidates found are genuine prompt muons. Since this purity is comparable to the 73% figure obtained using the muon chamber system alone, it is now possible to offer analysis teams a very flexible muon identification package based on using the muon chamber and HCAL selections in either "AND" (efficiency 41%, purity 84%) or "OR" (efficiency 85%, purity 66%) combinations. The efficiency of the "OR" selection, and the purity of the "AND" selection are shown in Fig. 15 as a function of momentum.

VI. OPAL Computing and Computing at Maryland

In 1987, the High Energy Group embarked on a program to expand its computing facility at Maryland. This was done in anticipation of the demand from the startup of the OPAL experiment at LEP. At that point, the computing power available to the group consisted of a VAX11/780, and a VAXstation II which were operated independently. The upgrade program started with \$400,000, to be spent over three years. The major technical improvement was to use the VAX11/780 as a bootnode in a VAXcluster configuration. More

Figure 15: Muon identification efficiency of the "OR" selection, and the purity of the "AND" selection as a function of momentum.

satellite nodes were added so that each physicist involved in data analysis has his or her own workstation. A 9600 Baud leased line was installed to connect the bootnode to Fermilab, which is the hub of the high energy physics network, HEPnet. To handle the large amount of data, disk storage was also increased.

By the end of the 1989-90 fiscal year, this first phase was completed. By then, the local area VAXcluster consisted of 11 VAX 3000 class workstations, and a VAX 6000-210 as the bootnode. The main disk storage was increased from 1.8 Gbytes to 7.8 Gbytes. The satellites and the bootnode are connected via Ethernet, while the storage devices are controlled by the bootnode via an HSC50. Thus we have a state-of-art configuration, well positioned for future expansion.

To satisfy the needs of Maryland physicists working at OPAL, two workstations were shipped to CERN.

During that period, the high energy group was expanded with new faculty members and students. Aside from OPAL, the group participates also in DØ at Fermilab, and SDC at SSC. The computing facility serves the needs of all these projects. It is also used by a Cosmic Physics Group headed by Prof. Goodman, and many of the theoretical physicists.

In fiscal year 1990-91, \$ 60,000 was spent in expanding the system. we purchased three more VAXstations and 6 Gbytes of disks. Two workstations have been sent to Fermilab to be used at DØ. More memory was added to three of the VAX3200 stations. In addition, one of the VAX3200 has been equipped with a CAMAC interface to be used as a data acquisition system for a muon chamber test station. This is a part of the SDC muon endcap chamber project.

The HEPnet link is also being upgraded to 56 kbaud, using a fractional T1 digital circuit.

In fiscal year 1991-92, \$ 54,000 was used to further improve the computing power and disk storage. We purchased three VAXstation 4000/M60's. One of them is to be installed at FermiLab for the use of the DØ experiment. We also purchased 13 Gbytes of disks. One of the existing VAXstation3100/M38 had its main memory increased from 8 Mbytes to 18 Mbytes.

For the next expansion, we plan to purchase two double density EXABYTE tape drives for DØ, one of which is to be installed at Fermilab. We also plan to purchase 19 Gbytes of disk storage.

The needs of the Maryland OPAL group at CERN for computing are modest for the coming year since we plan to make extensive use of common OPAL computing facilities. Currently the group has three VAX 3100 Model 30s, one VAX 3100 Model 76, and about two Gigabytes of disk space. In the coming year, we plan to purchase one additional workstation with one Gb of disk space (approximately \$15k). These stations are used for code development, test analysis jobs, and "ntuple" final data analysis. Full data analysis

takes place on the OPAL Shift facility (a system of networked Unix workstations and disk space). We are planning on the continued strong support of the DOE for the Indiana University effort in the Shift project. If that support is insufficient, then the Maryland OPAL group at CERN will have extensive additional need for computing resources at CERN.

In addition, simulation of the new silicon-tungsten forward calorimeter will require extensive computing resources (of the order of 1000 MIPS). At this time we anticipate these needs will be filled by either common OPAL facilities or other OPAL collaborators in the Si-W calorimeter project. There is some possibility that Maryland will be called upon to contribute computing resources to the simulation effort. If this happens, then an additional \$30K will be needed for three high CPU performance workstations to be used as part of a simulation "farm"

Calculation of Radiative Polarization Effects in Electron Storage Rings

Investigators: A. Skuja at the University of Maryland and L.N. Hand at Cornell University

A. Skuja and L.N. Hand Have calculated the Sokolov-Ternov radiation polarization levels for non-perfect electron storage rings, using quantum mechanical spin amplitudes to obtain transition rates for spin-flip electrons aligning themselves parallel or anti-parallel to the guide field of a storage ring during radiation emission. In the original calculations [1], the detector orbit was treated in a classical approximation, but the spin amplitudes and the emitted photon field were treated quantum mechanically without approximation, but in the non-relativistic (Foldy-Wouthuysen) limit. The calculation was generalized to take into account all "non-flip" photons [2] leading to both coupled and uncoupled depolarization resonances.

Professors Hand and Skuja are now calculating spin-flip rates for magnetic configurations other than a constant field. They have submitted an abstract for such a calculation in a magnetic undulator for the upcoming Hamburg Accelerator Conference (July 20-24, 1992).

References

- [1] L.N. Hand and A. Skuja, "Macroscopic Quantum Mechanical Contributions to Radiative Polarization in Electron Storage Rings", Phys. Rev. Lett. **59**, 1910 (1987).
- [2] L.N. Hand and A. Skuja, "The QED Calculation of Spin Orbit Coupling Resonances in Electron Storage Rings ", Phys. Lett. **A139**, 291 (1989).

Section B:
Hadron Collider Physics at Fermilab

The University of Maryland High Energy Physics Group has been involved in the DØ experiment since its inception at a moderate level. (S. Kunori and P. Rapp). Our involvement has increased considerably since 1987, when Prof. N.J. Hadley joined our group. In 1988 Prof. A. Baden joined the University of Maryland. He initially worked to finish his Top search analysis and b-physics analysis for CDF. This work is now complete and he is concentrating on the startup of DØ in 1992.

We have one post-doctoral physicist (Kathy Streets) working on the DØ experiment, and we are in the process of hiring another post-doctoral physicist for this experiment.

DØ Experiment at the Tevatron Collider

The collaboration: A. Baden, N.J.Hadley, S.Kunori, K. Streets, D. Norman, R. Snihur at the University of Maryland in Collaboration with Universidad de los Andes, the University of Arizona, Brookhaven National Laboratory, Brown University, University of California at Riverside, Centro Brasileiro de Pesquisas Fisicas, CINVESTAV, Columbia University, Delhi University, Fermilab, Florida State University, University of Hawaii, University of Illinois at Chicago, Indiana University, Iowa State University, Lawrence Berkeley Laboratory, University of Michigan, Michigan State University, New York University, Northern Illinois University, Northeastern University, Northwestern University, University of Notre Dame, Panjab University, Purdue University, University of Rochester, CEN Saclay, IHEP Protvino Russia, State University of New York Stony Brook, Tata Institute Bombay India, University of Texas Arlington, Texas A&M University

Introduction

The DØ experiment, which is being built by a collaboration of more than 300 physicists from 34 institutions, is a large 4π detector facility designed to study proton-antiproton collisions at 2 TeV center of mass energy. Since DØ has no magnetic field, it is able to have compact, highly segmented, nearly hermetic calorimetry with excellent energy resolution. It also has excellent lepton identification for both electrons and muons. We hope to use the strengths of DØ to:

1. Study the physics of QCD, in particular that of jet production, at the highest energy accelerator in the world.
2. Search for phenomena that are predicted to exist by the Standard Model but have not yet been observed, most notably the top quark.
3. Search for phenomena that lie beyond the standard model, such as supersymmetry and technicolor.

The DØ experiment has been under construction during 1991 and 1992. The central calorimeter (See Figure 16 for a drawing of the DØ calorimeters) and all of the elements of the central detector, the Central Drift chamber, the Transition Radiation detector, the Forward Drift chambers, and the Vertex detector, are now complete. The muon iron is in place and the muon chambers are installed in the detector. Quite simply, the entire apparatus is now complete. The detector has been rolled into place in the Tevatron and we expect to start taking colliding beam data within a month.

During this year there have been a number cosmic ray commissioning runs, and we calibrated calorimeter modules and parts of the central detector in a Test Beam at Fermilab during the latest fixed target run. The goal of all of these efforts was to be ready to take data during the Fermilab collider run which is now scheduled for May 1992.

The University of Maryland DØ group remained essentially the same size during 1991 and early 1992. We are now 4 Ph.D.'s (Prof. Baden, Prof. Hadley, Dr. Kunori, and Dr. Streets) and two full time graduate students (Mr. Norman and Ms. Snihur). We are in the process of hiring an additional postdoc. The Maryland group has hardware responsibilities for the construction of the DØ high voltage fanout and current monitoring system. The group has software responsibilities for the development of muon analysis programs and for jet reconstruction algorithms. We have also been heavily involved with the calorimeter test beam effort, with the testing of calorimeter electronics, and with the study of the DØ trigger.

Cosmic Ray Commissioning Run

We have just finished another successful cosmic ray commissioning run this time of both the central and endcap calorimeters. In Figure 17, we show a plot of a cosmic ray as seen in the central and endcap calorimeters. During this run, the DØ trigger and data acquisition system performed as expected and the calorimeters continued to perform well.

Calorimeter Test Beam

A test beam has been used by DØ in the past several fixed target runs at Fermilab in order to calibrate the calorimeter. It is very important to the DØ experiment to establish an absolute energy calibration of the calorimeter modules and then to transfer this calibration to DØ. The test beam was also used to determine the optimum high voltage operating point, to understand effects of argon contamination, and to understand detector resolution. We measured the uniformity of response of the modules and effects due to cracks, spacers, and bolts. We measured the shower shapes in order to tune the Monte Carlo. The overall operation of the experiment including the data acquisition system, calorimeter electronics and online software was exercised in the test beam. This test beam work is a large effort and involves many of the member institutions in the DØ collaboration.

During the 1990 fixed target run at Fermilab, we studied the endcap electromagnetic, inner hadronic and middle hadronic modules using e^- , π^- , and μ^- beam particles from 5 to 150 GeV/c in the DØ test beam. This run was completed in December 1990 and results will be submitted to NIM soon.

The modules performed as expected with an electromagnetic sampling resolution of $15.7\%/\sqrt{E}$ and a constant term of 0.3% and with a hadronic sampling resolution of $45\%/\sqrt{E}$ with a constant term of 4%. The calorimeter response was measured to be linear to within 0.5% and to have an electromagnetic to hadronic response ratio of between 1.02 and 1.09 from 10 GeV to 150 GeV. Figure 18 shows pulse height distributions of electrons for various beam energies, normalized to the same number of events. Figure 19 shows (a) mean pulse height as a function of beam energy, (b) fractional residuals from a linear fit, and (c) fractional energy resolution as a function of beam energy for electrons. Figure 20 shows the hadronic resolution as a function of pion beam energy, with and without a cut on electromagnetic layer $1 < 0.38$ GeV. Monte Carlo points are also shown.

Figure 16: The DØ calorimeters

Figure 17: Cosmic ray event in D0 calorimeters

Figure 18: Pulse height distributions of electrons as a function of beam energy

Figure 19: (a) mean pulse height as a function of beam energy, (b) fractional residuals from a linear fit, and (c) fractional energy resolution as a function of beam energy for electrons

Figure 20: The hadronic resolution as a function of pion beam energy, with and without a cut on electromagnetic layer 1 < 0.38 GeV

During the 1991 fixed target run at Fermilab, we studied the central calorimeter electromagnetic, fine hadronic, and coarse hadronic modules and also the endcap middle and outer hadronic modules. The modules were configured in the same way as they will be at DØ. Massless gaps and inner cryostat detectors were also in place to determine amount of energy lost between the two different types of modules. Figure 21 shows the layout of the modules in the cryostat. Data was taken with e^- , π^- , and μ^- beam particles from 2 to 150 GeV/c. This fixed target run was from July 1991 to January 1992.

K. Streets from the Maryland group was in charge of commissioning and maintaining the calorimeter electronics for the both test beam runs. Her responsibilities included installing, debugging, maintaining and studying the operation of the electronics during the run, with the help of several graduate students, including D. Norman from Maryland. The monitoring and fixing of any problems with the calorimeter electronics was a large effort.

The mapping of module readout pads to calorimeter electronics channels was done by mapping the layout of the 2300 channels onto appropriate places on the feedthru boards which take the signals out of calorimeter. The signals then were mapped through the preamp box and base-line subtractors(BLS) and then to analog-to-digital converters(ADC). Data files had to be written for each different module and for each step of the path. Software was written to read these data files and correctly map from the eta, phi and layer addresses of the module readout pads to the electronics coordinates and then to write out the final mapping tables. A translation program in the form of a grid was written to show the mapping in detail from any module readout pad to its readout channel in the electronics. This program was used by the collaboration throughout the run.

Work was done in adding new features to the calorimeter online analysis code (CALELEC). It was changed to handle zero suppressed data and update it as needed for the test beam and also for DØ studies. A DØ note called "Calorimeter Electronics Testing Using Examine2" was written by K. Streets (#1144) describing how to run the program and its different features. Different versions of CALELEC were written to study the operation of zero suppression, switching between zero-suppressed and non-zero-suppressed readout during a run, to look for stuck bits in the adc, analyse pulser runs to determine dependence on preamp and Base line Subtractor Card (BLS) temperature, analyse pulser runs to determine electronics linearity, to study pedestals taken during beam spills and to study how to correct zero suppressed data. Many of these studies were done by the Maryland group and some will be described below.

The linearity of the calorimeter electronics was examined in detail by K. Streets and D. Norman. Fifteen runs with pulser amplitude and attenuation settings over the entire range of low gain setting (x8) were taken and then fit to a straight line to determine the attenuation factors and the amount of ADC counts when pulser amplitude was zero. These numbers are needed for the gain calculation of electronics at DØ. The electronics were found to be linear within 1% except at very low ADC counts (< 100 MeV) Figure 22 shows ADC counts versus pulser settings and figure23 shows the fractional residuals versus pulser settings for a single ADC channel.

Figure 21: Layout of the hadronic calorimeter modules in the cryostat

Figure 22: ADC counts versus pulser settings

Figure 23: Fractional residuals versus pulser settings for a single ADC channel

Studies were done to check the pedestals and gains calculated by the program CALIB of the calorimeter electronics channels. CALIB had been used to calculate all previous pedestals and gains. The CALIB pedestal runs were checked by comparing the pedestal values with results for pedestal averages obtained by analysing the exact same events from the pedestal run with the program CALELEC. The CALIB pedestal values were found to be different from the values of straight averages (no events removed from sample) from CALELEC by about 0.07 ADC counts. This error can add up to be as large as 1 GeV when summing over all channels to calculate the energy in a shower. It was found to be due to the fact that CALIB removed events outside a tight window around the pedestal distribution before calculating the averages and thereby skewing the results. This problem has now been corrected for DØ. The gain runs in the database had to be corrected for problems found later due to an unterminated input from a pulser signal and also due to differences in pulser output due to capacitance. The amount to correct the database by for the unterminated pulser input problem was determined by using the program DBL3STUDY. The corrected databases were also checked using this program. A few problems were found but quickly fixed by this method.

Work is in progress for studying the effects on the data from zero suppression. A procedure to correct zero suppressed data was determined and the software to implement and test this procedure has been written. Zero suppressed data has all channels with values which are below a predetermined cutoff (usually about $2 \times$ pedestal sigma) not readout. Corrections to zero suppressed data for the effect due to placing symmetric cutoffs around an asymmetric pedestal distribution are determined using a pedestal run. This correction is determined channel by channel and is the average value of all events inside the cutoff values, i.e. the events that would be removed in a zero suppressed run. This correction was determined to be -0.17 ADC counts on average. The algorithm to apply these correction factors to zero suppressed runs was tested first on a pedestal run and then applied to beam runs. After applying the corrections, the difference in energy between zero suppressed and non zero suppressed runs is just the energy lost in the tails of the shower by zero suppressing. Preliminary results show this energy loss to be on the order of 1%. This energy loss will be mapped out and applied to data at DØ eventually.

Pedestal dependence on temperature was also studied. Preliminary results show no dependence of pedestal values on preamp temperature but that there is a correlation with BLS temperatures of ≈ 0.08 ADC counts per $^{\circ}\text{C}$. Figure 9 shows the average pedestal values over a BLS crate for runs taken over a month's time versus the BLS temperatures in that crate.

An analysis of energy scan data was performed in order to find the optimum roadsize (number of eta cells by number of phi cells to sum) to use in the energy calculation. Runs were analysed using a variety of roadsizes to determine at which point the energy was fully contained. It was determined that for a 50 GeV pion run, the energy in the shower is $> 99.5\%$ contained in a roadsize of 10 eta by 10 phi cells. For a 50 GeV electron run, a 4 eta by 4 phi cell size road was enough to fully contain the energy without adding in additional noise. Figures 25 and 26 show the pedestal corrected mean energy in ADC counts versus

Figure 24: Average pedestal values over a BLS crate for runs taken over a month's time versus the temperatures in that crate

the roadsize for the pion and electron runs respectively.

Preliminary results of the calorimeters tested in this run give an energy resolution of $13\%/\sqrt{E}$ with a constant term of 0.9% for electrons and $44\%/\sqrt{E}$ with a constant term of 5% for hadrons, which agrees with expected results. Analysis to determine the linearity, uniformity, and to transfer the calibration to the DØ detector is currently underway.

High Voltage Fanouts

The Maryland group is responsible for building most of the DØ high voltage fanouts and for designing and building high voltage fanouts with current monitoring for the DØ calorimeters. We have built all of the more than 5000 channels of high voltage fanouts and patch panels needed by DØ. Despite our only becoming involved with this project in June of 1989, we completed these fanouts in time for use in the test beam and the cosmic ray commissioning test as well as for general debugging of various detectors in DØ. The fanouts without monitoring met the specification of less than 2 nanoamps of leakage current at 10,000 volts. They were built and tested at Maryland by our group's electronics engineer and technical staff, using the services of the Maryland Physics Department machine shop.

The construction of the fanouts with current monitoring for the DØ calorimeters is also complete. The current monitors are computer controlled and are capable of reading from 100 nanoamps to 16 microamps at 2800 volts. The design and testing were again accomplished by the High Energy Physics group's electrical engineer (R. Bard) and technical staff (W. Miller and J. Colmer) with the assistance of Prof. Baden and graduate student, R. Snihur. Current monitoring was implemented on about 512 out of a total of 2500 calorimeter channels to reduce the cost. The fanouts were built in such a way that current monitoring can be added later when more funds are available.

During the past nine months, we built a small number of additional fanouts and patch panels, and modified others as needs changed.

The work on the high voltage fanouts is funded by DØ equipment monies which are transferred to Maryland through Fermilab.

Trigger Studies

During the last nine months, we have begun to devote a larger and larger fraction of our time to studying and commissioning the DØ trigger. This, of course, is a large task involving many groups from DØ. One of us, N. Hadley, serves on the DØ Trigger Panel which is charged with determining the trigger configuration for the DØ experiment during Physics data taking. The DØ trigger is designed as a multi-stage trigger where each stage reduces the rate sufficiently so that subsequent stages which take longer time have minimal deadtime. Level 0 is an inelastic interaction trigger based on hits in scintillators mounted on the End calorimeter cryostats. The Level 1 trigger operates within the bunch crossing time of $3.5\mu\text{sec}$ and uses hardware calorimeter and muon hits. The hits can be combined to

Figure 25: ADC counts versus roadsize for pions

PEDESTAL CORRECTED MEAN ENERGY IN ADC COUNTS

50 GeV ELECTRON RUN

Figure 26: ADC counts versus roadsize for electrons

require combinations of various objects. For example, a specific level 1 trigger could require one EM calorimeter tower above 10 GeV and two muon candidates. The experiment can have upto 32 different Level 1 triggers running at once. Some hardware triggers require more than the $3.5\mu\text{sec}$ between beamcrossing to make their decision. these are called Level 1.5 triggers. Muon candidates with a Pt cut and the TRD trigger are both Level 1.5 triggers. The Level 2 trigger is built from a farm of 50 microvaxes that serve as the software event filter. The raw inelastic interaction rate at $10^{30} \text{ cm}^{-2} \text{ s}^{-1}$ is about 50KHz. The rate out of Level 1 is expected to be 200 Hz or less. The rate out of level 2 should be a few Hz.

We have helped debug the Level 2 tools for finding electrons, jets, muons and missing Pt. We have worked on the process of determining a list of Level 1 and Level 2 triggers that is efficient for all of the Physics we desire to explore with DØ while at the same time satisfying the rate limitations out of Level 1 and Level 2 given above. As an example, we show in figures 27 and 28 the cross section out of Level 1 and Level 2 as a function of missing Pt. Missing Pt triggers are used for studying W's and for searching for the Beyond the Standard Model Physics. This rate is calculated from a sample of QCD background events generated with ISAJET. In Figure 29, we show the cross section out of Level 2 plotted as a function of missing Pt for the Minimal Supersymmetric Standard Model (MSSM) with a 150 GeV gluino and a 500 GeV squark. We note that the process of determining a list of triggers for DØ is far from over and will undoubtedly continue to change as we start to take data.

Physics Analysis

The DØ experiment will address a wide range of physics topics. DØ analysis has been split into four physics groups, electroweak, top, bottom, and QCD/New. The "New" here refers to all beyond the standard model. In addition to the physics analysis groups, there are also four particle algorithm groups, electron/photon, muon, jets and missing Pt. In what follows, we will briefly discuss some of the aspects of the physics analysis that the Maryland group has worked on directly.

N.Hadley and B. Klima from FNAL are the co-leaders of the DØ Jets Algorithm group. The collaboration uses both a cone algorithm and a nearest neighbor algorithm. The jet algorithms have been stable for more than a year now, and have been used to analyze many hundreds of thousands of Monte Carlo events. We continued work on a theoretical understanding of the jet cross sections using a QCD calculation program written by S. Ellis, Z. Kunszt, and D. Soper [1].

We did a large number of studies on looking for supersymmetric particles and leptoquarks with DØ. These included studies of backgrounds as well as studies of the signatures for possible signals.

We investigated searching for the top quark in the lepton plus jets channel.

We worked on the muon reconstruction program and muon Monte Carlo simulation

Figure 27: The cross section out of Level 1 as a function of missing Pt.

Figure 28: The cross section out of Level 2 as a function of missing Pt.

Figure 29: The cross section out of Level 2 plotted as a function of missing Pt for the Minimal Supersymmetric Standard Model (MSSM) with a 150 GeV gluino and a 500 GeV squark

program.

DØ Upgrade

The DØ collaboration is presenting to the Fermilab PAC in July of 1992 a detailed plan and costing for upgrading the detector. Highlights of the upgrade include:

1. Enable triggering with 400 ns (or maybe even 133 ns) times between bunch crossing;
2. Enable detector running for the high luminosity (and high radiation) environment produced by the Tevatron upgrade and Main Injector installation;
3. Installation of a superconducting solenoid for electron and muon identification as well as for complementing a high precision central and forward silicon tracking system;
4. Upgrade of the hardware and software triggers for the increased rate.

The co-leaders of the DØ upgrade (called DØβ) have asked Dr. Baden to take the lead in developing a plan for upgrading the trigger and data acquisition (T/DAQ) system. The design currently being considered is driven by the physics goals of being able to exploit the FNAL Tevatron/MI upgrade for b physics. Since b -quark production peaks at transverse momenta of order the b -quark mass ($\sim 5\text{ GeV}/c^2$), with the average lepton p_t a few GeV/c^2 lower, an upgrade to the trigger design will have as its goal triggering on low- p_t inclusive leptons as close to the b mass as possible and even lower for di-leptons. These rates overwhelmingly dominate the rates for high- p_t physics such as electroweak, top, SUSY, compositeness, *etc.*, and pose non-trivial challenges in T/DAQ. For example, the cross-section for $b\bar{b}$ production at 1.8 GeV $p\bar{p}$ is of order $50\mu\text{b}$. Each b quark decay reduces the rate by approximately 10%, giving the inclusive electron rate from bottom at $5 \times 10^{31}/\text{cm}^2/\text{s}$ (or equivalently $50\mu\text{b}^{-1}/\text{s}$) to be 500Hz in the detector. Using a conservative tagging efficiency of 5% (which includes both a fiducial volume cut and a transverse energy threshold of order 5 GeV) this rate is reduced to of order 25 Hz. However, calculations indicate that the background from γ conversions will dominate the inclusive electron acceptance rate at the hardware trigger by between 30 and 300 to 1, resulting in of order 1kHz into the DØ level 2 online processor farm trigger. The inclusive muon rate, especially in the forward direction, will have similar signal-to-background ratios (dominated by decay-in-flight of charged K/π).

The present DØ (called DØα) T/DAQ system consists of

- Level 1 hardware trigger: for e , ν , and jet triggers, combining physical towers in the calorimeter into larger "trigger" towers for threshold comparisons using decreased resolution (8 as opposed to 12 bit ADCs) - for μ triggers, requiring coincidences in the muon chamber roads (no momentum cut);

- Level 1.5 hardware trigger: TRD track match with previous e trigger - use of muon chamber hits for crude spectroscopy for μ triggers;
- Level 2 processor trigger: Parallel DAQ data cables from front-end VME ADC crates feeding into multiport memory boards inside VME level 2 crates attached to approximately 600 Vax MIPs of processing.

The bandwidth limit into Level 2 is approximately 200 Hz (with 250kByte events sizes). With a slight increase in the number of data cables and proper load balancing of crates per cable, we can achieve a modest incremental upgrade of the $DØ\alpha$ DAQ system that will reach rates of order 500 Hz, perhaps more. However, since we will be background dominated, most of the Level 2 nodes in $DØ\beta$ will be rejecting (background) events. Also, with the magnetic field, the tracking and fitting algorithms will increase in complexity and cpu time required, and we will need to upgrade the Level 2 cpu capability. To estimate the amount of cpu needed for $DØ\beta$, we use 500-1000 MIPs-sec/event (or 500 million instructions per event) on a VAX 11/780 (a number consistent with CDF results) as the amount of cpu needed to process a single event, dominated by full track reconstruction. For Level 2, we can order event cuts (e.g. place cuts on calorimeter variables before tracking) and implement a tracking algorithm which employs region tracking surrounding the lepton candidate to reduce this cpu requirement by a factor of order 10. If we then have of order 500 Hz into Level 2, then we will need 500 events/sec $\times$ 500 - 1000 MIPs-sec/event = 25 - 50 kMIPs. Current industry projections of approximately \$100/MIP for 1995-7 technology (see SDC Technical Proposal to DOE/SSCL) would place the cost of the $DØ\beta$ Level 2 processor farm at approximately \$2.5-\$5.0M. It is therefore advantageous to put resources into reducing the rates into Level 2 where rejection in the hardware trigger is much more expensive.

Dr. Baden has calculated the increase in the calorimeter Level 1 trigger rejection by increasing (in hardware) the number of trigger towers (or equivalently, by decreasing the physical tower to trigger tower ratio, currently 4 to 1, each trigger tower subtending $.2 \times .2$ in $\eta\phi$ space). Figure 15 indicates that the rejection closely scales with the decrease in the size of the trigger tower. More calculations using the full DØGEANT Monte Carlo are currently being done.

A further upgrade to the trigger will have to take place at the front-end VME crate level where one finds the Level 1.5 trigger, ADC cards VME Bus Drivers (VBD cards), and DAQ front-end controllers. Dr. Baden has proposed a scheme for upgrading the electron trigger whereby the front-end VME crate VBD cards (which pull data from the ADC cards into internal memory and push it once assembled onto the data cables headed up to Level 2) are upgraded by the following scheme:

- Increase memory capacity to allow event buffering - since each crate reads out a fraction of the entire $DØ$ data (approximately 10 kBytes/crate averaged over all crates), this should be relatively inexpensive;

Section C:
**Fixed Target Physics
and Particle Physics of General Interest**

In 1981, after the PLUTO experiment at DESY finished taking data, several members of the University of Maryland High Energy Physics Group (S. Kunori, A. Skuja, G. A. Snow, and P. Steinberg) joined the muon deep inelastic scattering experiment being planned for the TeV II program at Fermilab. This choice reflected Prof. Skuja's long involvement with the previous series of muon experiments at Fermilab, as well as the work done by Dr. Kunori and Professors Snow and Steinberg on neutrino scattering in Deuterium. At that time, the experiment was scheduled to take data in 1985/86. However, the experiment was delayed for two years because of the Fermilab construction program to install D0. The initial delay produced a further delay in data analysis because of diminished manpower at Fermilab. Many of our collaborators who had made plans to be at Fermilab during data taking and for the subsequent year had to return to their home institutions before any data was actually taken. Many results from the 1987 run have been reported at national and international meetings and are now being published.

Prof. C. Y. Chang decided to work with the Maryland Cosmic Ray group to detect extraterrestrial ultra high energy photons (> 100 TeV). An air shower array was constructed at Los Alamos in 1985 and the CYGNUS collaboration was formed. Prof. Chang plans to continue with this endeavour in the future.

Prof. N. J. Hadley joined the University of Maryland in 1988. At that time, he was working on rare Kaon decays at BNL. He finished this work in 1989 and went on to lead our involvement on D0 at Fermilab. Most results have now been published, and are briefly discussed.

Prof. Talaga was at Maryland from 1982-88. During this period, he worked on the $\nu_e e^-$ elastic scattering experiment (E225) at Los Alamos. Final interpretations of the results from this experiment are still being published.

In addition, a visitor to our department, Dr. D. C. Peaslee, has organized a summer school in Hadron Spectroscopy at Maryland every year for the last four years.

Muon Deep Inelastic Scattering (E665) at Fermilab

Collaborators: S. Aid (now in France), S. Kunori, S. O'Day (now at FNAL), E. Ramberg (now at FNAL), A. Skuja and G. A. Snow at the University of Maryland in collaboration with Argonne, California (San Diego), Crakow, Fermilab, Freiburg, Harvard, Illinois (Chicago Circle), Livermore, Max Planck Institute (Munich), MIT, Northwestern, Ohio, Pennsylvania, Washington, Wuppertal and Yale.

The Fermilab experiment E665 has been studying the structure of nuclei as well as nucleon and hadron production processes in deep inelastic scattering using muons as projectiles. The muon beam has an energy of 500 GeV, the world's highest. The experiment has taken data in three fixed target running periods at Fermilab although the initial engineering run was in the summer of 1985. The first data run occurred in 1987-88, the second in 1990, and the third and last was completed at the end of 1991. Results from the initial data run have been presented at various conferences and many papers have been submitted for publication. Three Maryland graduate students have received their Ph.D.'s based on work done on the E665 experiment.

First Run (1987-88 run)

The E665 apparatus, as used in the first run, is shown in Figure 30. The muon beam impinges on a target located inside a streamer chamber and placed within a superconducting magnet, the CERN vertex magnet (CVM). The muon beam momentum is measured by a 55 meter long beam tagging station, not shown in the figure, and sometimes referred to as the Beam Spectrometer. Momenta of energetic secondary charged particles as well as the scattered muon produced by interactions in the target (and elsewhere) were measured by the forward spectrometer. The Forward Spectrometer consisted of proportional chambers before and inside the superconducting Chicago Cyclotron Magnet (CCM) as well as drift chambers after the magnet. Low energy particles were measured by the Vertex Spectrometer that included wire chambers in addition to the streamer chamber. Energies of photons and electrons were measured by an electromagnetic calorimeter, built by the Maryland and Harvard groups, downstream of the forward spectrometer. This large 3m by 3m electromagnetic calorimeter is one of the unique features of the experiment, since it provides excellent energy and position measurement for high energy photons. All particles but muons were absorbed in a 3 meter thick iron absorber behind the forward spectrometer and the electromagnetic calorimeter. The scattered muon was detected and its direction measured by a series of scintillation counter and wire tube chamber planes, placed downstream of the absorber. The Muon Detector was the major component used in the trigger and in muon identification. A time of flight counter system and three Cherenkov counters were also installed for particle identification. A novelty of the experiment is the large RICH counter used in the Forward Spectrometer for particle i.d. More details of the apparatus may be found elsewhere [97].

Figure 30: The E665 Detector

Three targets – liquid hydrogen, liquid deuterium, and high pressurized gaseous xenon – were used during the first run. Data were taken for about a month with each target. Two main triggers were implemented in addition to many monitoring triggers. The large angle trigger (LAT) covered the muon scattering angle down to roughly 3 mrad. The small angle trigger (SAT) reduced this angle down to 1 mrad but used only 12% of the beam.

In the 1990 run data was taken with many nuclear targets, alternating rapidly, including deuterium. In 1991, data was taken with H_2 and D_2 targets only.

All of the usable data from the first run have been processed through the reconstruction programs. Also, most of the streamer chamber pictures have been measured. The Maryland group made many contributions to establish the software system and had a leading role in the data analyses (as reported in previous Progress Reports). The initial data analysis took longer than expected because the limited number of tracking chambers in the experiment made efficient pattern recognition somewhat difficult.

Since E665 uses the world's highest muon beam energy, it covers a much wider kinematical range compared to other muon scattering experiments. We access the Bjorken scaling variable (x_{Bj}) between 10^{-5} and 1, the four momentum transfer (Q^2) between 0.1 to 100 GeV^2 , and the hadronic total energy (W) up to 32 GeV. With this wide kinematical range, we can measure events from the nearly real photon region to the deep inelastic region. In addition, at small x_{Bj} and high W , contributions from gluons inside the nucleon become an important component of the cross section. We were thus able to study jets from the gluon fusion process and measure the gluon distribution inside the nucleon for the first time.

In the following discussion of physics results, four topics will be highlighted:

- a. QCD Effects Observed in 490 GeV/c Deep Inelastic Muon Scattering (165)
- b. First Measurements of Jet Production Rates in Deep Inelastic Lepton-Proton Scattering (164)
- c. Shadowing in Muon-Xenon Inelastic Scattering at 490 GeV/c (166)
- d. First Observation of the Saturation of Shadowing at Very Low x_{Bj} (167)

a. QCD Effects observed in 490 GeV/c Deep Inelastic Muon Scattering

Results on forward di-jet production in 490 GeV/c deep inelastic muon scattering on hydrogen and deuterium targets have been obtained. The transverse momenta, azimuthal symmetry and energy flow of events with ≥ 4 charged hadrons have been studied. The range of the invariant hadronic mass squared $100 < W^2 < 900 \text{ GeV}^2$ is the largest yet achieved by a deep inelastic scattering experiment. Data are compared to the predictions of the

Lund Monte Carlo with hard QCD simulated by matrix elements, parton showers and color dipole radiation. Fig. 31 shows the Feynman diagrams for deep inelastic scattering to first order in hard QCD. Notice that a class of diagrams appear, called photon-gluon fusion, that do not appear in $e^+e^- \rightarrow \text{multijet}$ events, which have already been well studied, particularly at LEP.

Figure 32 displays the observed W^2 distribution after kinematic and quality cuts. These events were triggered with the large angle trigger (LAT). Only forward going charged particles ($\chi_F > 0$) are included and the other cuts are $60 < \nu < 500 \text{ GeV}$, $Q^2 > 3.0 (\text{GeV}/c)^2$, $0.1 < y < 0.85$, and $x_{Bj} > 0.003$.

Hard QCD events tend to give more particles at higher transverse momentum in the plane of the μ scattering than in the perpendicular direction. This is clearly seen in Fig. 33(a) and Fig. 33(b) where the observed p_T^2 distributions "in" and "out" of the μ scattering plane are displayed and compared with the Lund Monte Carlo prediction. In this Monte Carlo the Morfin and Tung structure functions have been used for the target nucleons. It is clear from Fig. 33(a) that a hard QCD component is essential to fit the data.

To further investigate the p_T distributions, it is useful to introduce two other event variables:

$$\Pi = \frac{4}{\sqrt{N_T}} \Sigma(|p_T| - p_{T^0})$$

and the planarity,

$$P = \Sigma(p_{T^2, in}^2 - p_{T^2, out}^2) / \Sigma(p_{T^2, in}^2 + p_{T^2, out}^2).$$

The constant $p_{T^0} = 0.32 \text{ GeV}/c$ moves the most probable value of the distribution to zero and the square root of the number of charged hadrons, $\sqrt{n_T}$, renders the distribution independent of multiplicity. Fig. 34 shows a comparison of data with theory for the normalized Π distribution, corrected for acceptance. Again the agreement with the QCD prediction is very good. Events with large values of the Π variable should show evidence of two jet behavior. This is seen in Fig. 35(a) and (b) in the comparison of the angular energy flow for events 6(a) with $\Pi > 3$ as compared with events 35(b) with $\Pi > -1$. The double peaked distribution in Fig. 35(a) is strongly suggestive of two hadronic jets being produced in the forward hemisphere.

b. First Measurements of Jet Production Rates in Deep Inelastic Lepton-Proton Scattering

In this paper the first measurements of forward multi-jet rates in deep inelastic lepton scattering are presented. Data were taken with the 490 GeV muon beam incident on a

QUARK
SCATTERING

GLUON
BREMSTRAHLUNG

PHOTON-
GLUON
FUSION

Figure 31: Feynman diagram for deep inelastic scattering to first order in hard QCD

Figure 32: The uncorrected W^2 distribution for the data sample after the kinematic and quality cuts

Figure 33: Normalized Σp_T^2 , in and Σp_T^2 , out distributions for events with $W^2 > 300 \text{ GeV}^2$ and ≥ 4 charged hadrons. The data are corrected for acceptance

Figure 34: Normalized Π distributions for events with $W^2 > 300 \text{ GeV}^2$ and ≥ 4 charged hadrons. Data, which are corrected for acceptance, are compared to predictions of the Lund Monte Carlo

Figure 35: Energy flow profiles for events with $W^2 > 300 \text{ GeV}^2$, $P > 0.5$ and two Π cuts
 (a) $\Pi > 3$, (b) $\Pi > -1$. The data are corrected for acceptance

hydrogen target. The jets were defined using the JADE algorithm. The measured rates are presented as a function of the jet resolution parameter Y_{cut} and as a function of the virtual photon-proton center-of-momentum energy W in the range $13 \leq W \leq 33$ GeV.

The event sample satisfied the kinematic cuts: $Q^2 > 4.0(\text{GeV}/c)^2$, $\nu > 40\text{GeV}$, $x_{Bj} = Q^2/(2M_\nu) > 0.003$ and $0.05 \leq \nu/E_{beam} \leq 0.95$. Coherent photon bremsstrahlung events were removed and only particles, both charged and neutral, going forward in the virtual photon-proton center-of-momentum system were considered. After a few quality cuts we were left with a sample of 12,573 events with $W \geq 13$ GeV. The average observed multiplicity was 6.6 particles per event (2.3 charged plus 4.3 neutral).

The JADE algorithm to define a jet is as follows. One calculates for every pair of particles i and j the quantity

$$Y_{ij} = \frac{M_{ij}^2}{W^2}, \text{ where } M_{ij}^2 = 2E_i E_j (1 - \cos \Theta_{ij})$$

Then if $Y_{ij} < Y_{cut}$, particles i and j are combined into one jet. The jet distribution can be studied as a function of the value of Y_{cut} in various bins of W . This is shown in Fig. 36. As one expects, the multiple jet sample increases as Y_{cut} decreases. Choosing the value of $Y_{cut} = 0.04$ (a common value for e^+e^- jet analyses), one can investigate the scaled energy flow of the two jet vs. one jet events. This is shown in Fig. 37. A two-lobed and broader structure is observed in the two jet sample.

Fig. 38 shows the forward di-jet rate versus W for a value of $Y_{cut} = 0.04$. As predicted by leading order perturbative QCD, the forward di-jet rate falls as W increases. Good agreement is observed with the QCD based models, with the naive QPM prediction excluded. The drop in the rates as a function of W can be explained by three effects. The first is purely kinematical; for a fixed Y_{cut} , increasing W implies an increasing cut on the effective invariant mass of the hadrons. The second is the running of the strong coupling constant, and the third is the variation of the parton distribution functions with W (i.e. x_{Bj} and Q^2). Further work is needed to resolve the relative importance of these effects as well as the sensitivity of these results to α_s and to the parton distributions.

c. Shadowing in Muon-Xenon Inelastic Scattering at 490 GeV/c

Inelastic scattering of 490 GeV μ^+ from deuterium and xenon nuclei has been studied for $x_{Bj} > 0.001$. The ratio of the xenon/deuterium cross section per nucleon is observed to vary with x_{Bj} with a depletion in the kinematic range $0.001 \leq x_{Bj} \leq 0.025$ which exhibits no significant Q^2 dependence. The electromagnetic calorimeter was used in a crucial way to verify the large radiative corrections.

Figure 36: Forward jet rates for one jet (open circles), two jets (solid circles) and more than two jets (open triangles) versus Y_{cut} for different W bins (a) $13 \leq W \leq 18$ GeV, (b) $18 \text{ GeV} \leq W \leq 23$ GeV, (c) $23 \leq W \leq 28$ GeV, (d) $28 \leq W \leq 33$ GeV. The data have been corrected for acceptance, resolution and reconstruction efficiency. Lund model predictions are also shown (matrix elements (solid curve) and parton showers (dashed curve))

Figure 37: The energy flow per event for the one- and two-forward jet samples with $Y_{cut} = 0.04$. ψ is the angle between the virtual photon direction and the hadron momentum projected into the hadronic plane

Figure 38: Forward di-jet rate versus W for $Y_{cut} = 0.04$. Lund model predictions are also shown (matrix elements (solid curve), parton showers (dot-dashed curve)). In addition, the results using the Quark Parton Model with no QCD corrections (dashed curve) are included

Theoretical models predict an onset of shadowing at $x_{Bj} \sim 1/2Mr$, where r = nucleon radius, and that this shadowing should begin to saturate at $x_{Bj} \sim 1/2MR$, where R = nuclear radius. It is important to study the small x_{Bj} region, that is with $x_{Bj} < 1/2MR$. In xenon this corresponds to $x_{Bj} < 0.02$. In E665, this can be achieved using energy transfers up to 300 GeV and Q^2 down to $0.1 \text{ GeV}^2/c^2$.

The data used in this study with xenon and deuterium used the small angle trigger (SAT) and consisted of 10276 xenon events plus 9914 deuterium events that satisfied the criteria: $E_{beam} > 400 \text{ GeV}$, $\nu > 40 \text{ GeV}$, $y = \nu/E_{beam} < 0.75$, $Q^2 > 0.1 (\text{GeV}/c)^2$ and $\chi_b > 0.001$. Fig 10 shows the variation of the yield of scattered muons from deuterium (black circle) and xenon (open circle) as a function of x_{Bj} . Events in the region $x_{Bj} = me/m_p = 1/1836$ originate from muon-electron elastic scattering. At still lower x_{Bj} the xenon data is dominated by bremsstrahlung which can be calculated analytically and can be measured directly with the electromagnetic calorimeter. The radiative corrections evaluated by the two methods agree quite well in the region of data presented here, $x_{Bj} > 0.001$.

The variation of the ratio σ_{Xe}/σ_D with x_{Bj} is shown in Fig. 39. E665's data confirm that the shadowing increases as x_{Bj} decreases at least until $x_{Bj} = 0.001$. Comparison is made with other experiments and with a similar measurement using real photons.

The Q^2 variation of σ_{Xe}/σ_D in the kinematic region $0.001 < x_{Bj} < 0.025$ is presented in Fig. 40. The data confirm that there is no evidence of explicit Q^2 dependence of σ_A/σ_D (down to Q^2 values of 0.1 GeV^2) when x_{Bj} is restricted to the shadow region.

d. First Observation of the Saturation of Shadowing at Very Low x_{Bj}

The ratio of cross sections for inelastic muon scattering on xenon and deuterium nuclei was measured at very low x_{Bj} ($0.00002 \leq x_{Bj} \leq 0.25$). Two largely independent analysis techniques gave statistically consistent results. The xenon-to-deuterium per nucleon cross section ratio is found to be constant at a value ≈ 0.7 for x_{Bj} below 0.003.

As has been shown in previous muon experiments (see Fig. 41) and in (c) above, the ratio of the inelastic per nucleon cross sections of heavy nuclei to deuterium decreases from unity as x_{Bj} decreases from 0.1 to 0.002. In addition the data at the lowest measured x_{Bj} tend toward the photoproduction data on heavy nuclei, although no evidence for saturation has been observed in previous inelastic scattering experiments. The aim of this experiment was to explore this conjectured saturation region by studying the ratio of xenon to deuterium per nucleon cross sections down to $x_{Bj} = 0.0002$, two orders of magnitude lower than any previous experiment.

Fig. 42 shows the event distribution as a function of x_{Bj} for the two targets after kinematic cuts, including $0.01 \leq Q^2 \leq 60 (\text{GeV}/c)^2$ and $|\Phi_{\mu} - \pi| \geq 0.2$. Significant electromagnetic backgrounds (i.e. bremsstrahlung, μe scattering), survive the kinematic cuts as is apparent

Figure 39: The x_{Bj} variation of the yield of scattered muons from deuterium (black circle) and xenon (open circle) targets. Events in the region $x_{Bj} = m_e/m_p = 1/1836$ originate from muon-electron elastic scattering

Figure 40: The x_{Bj} dependence of σ_{xe}/σ_D (black circle); error bars display statistical errors only. Systematic errors are estimated to be 7%. The Ca/D Structure function measurements from the NMC experiment (crosses) and the Fe/D measurements from E772 $\mu^+\mu^-$ experiment (open circles) are plotted for comparison. In addition, an interpolation of C, Cu and Pb 60 GeV photoproduction data to a xenon target and extrapolation to a photon energy of 150 GeV is indicated on the vertical axis

Figure 41: The Q^2 dependence of the $\sigma_{\pi e}/\sigma_D$ cross section measurement from the present experiment (black circle) for $0.001 \leq x_{Bj} \leq 0.025$. These data are compared to Ca/D structure function ratios (crosses) from the NMC experiment. Statistical errors only are shown for the E665 data which have an estimated 7% systematic error

Figure 42: The number of events from the (a) deuterium and (b) xenon targets versus x_{Bj} is shown. The solid histogram shows the distributions after the application of the kinematic cuts and the diagonally-striped histograms show the distributions after the electromagnetic cuts or hadron requirement

in Fig. 42. To separate these backgrounds from real inelastic events two essentially independent methods were used. One, a hadron requirement, demanded ≥ 2 positive tracks beside the μ^+ or at least 2 negative tracks fitted to the interaction vertex. Two, an electromagnetic cut, in which the event is rejected as background if $E_{\text{calorimeter}} > 0.45$ or if there was a coplanar energy deposit in the calorimeter with the incident and outgoing muons.

The two analysis techniques are compared in Fig. 43 which shows the Xe/D_2 per nucleon cross section ratio as a function of x_{Bj} . They are statistically consistent with each other with the electromagnetic cut data set somewhat more precise.

Fig. 44 compares the E665 Xe/D_2 cross section ratio with the results of NMC for the helium -, carbon -, and calcium - deuterium ratios and the photoproduction result interpolated to a xenon target and extrapolated to $\nu = 150$ GeV. For x_{Bj} below 0.003 the Xe/D_2 ratio is constant at $0.72 \pm 0.03 \pm 0.07$ and indicates a saturation in shadowing at very low x_{Bj} . The saturation value is also consistent with the photoproduction point at 0.60 ± 0.03 , derived for $\gamma - Xe$ scattering.

Figure 43: The ratio of the xenon and deuterium per-nucleon cross sections versus x_{Bj} as determined by the two analysis methods. The horizontal error bars show the bin width and the vertical error bars show the statistical uncertainty only. The ratio determined by the hadron requirement is displaced in x_{Bj} to make it easier to see the vertical bars

Figure 44: The ratio of the xenon and deuterium per-nucleon cross sections measured using the electromagnetic cuts is compared with the results of the NMC for helium, carbon and calcium targets and a photoproduction experiment interpolated to a xenon target and extrapolated to a photon energy of 150 GeV. The width of the shaded band represents the estimated systematic uncertainty of the E665 result with the x_{Bj} -dependent and $\pm 10\%$ overall systematic uncertainty added in quadrature

CYGNUS Experiment

Collaborators: C.Y. Chang at the University of Maryland in Collaboration with the University of California at Berkeley, Irvine, Riverside, and Santa Cruz, and the Iowa State University, Argonne National Laboratory, Los Alamos National Laboratory, Louisiana State University, University of Maryland (Cosmic Ray Group), George Mason University, New York University, and University of New Mexico.

Since its discovery in the early part of this century the source of very energetic cosmic rays has puzzled observers. Charged particles which make up the bulk of high energy radiation spiral toward earth in the magnetic fields which are omnipresent in the interstellar medium. This motion erases virtually all information about the particle's point of origin. However, cosmic gamma rays come to the earth directly from galactical sources so experiments that detect gamma rays have the ability to identify and study these sources. The integral flux of these energetic particles drops as $E^{-1.7}$ below several times 10^{15} eV and as $E^{-3.2}$ above that energy. The high energies involved require that detectors be massive, which makes ground based detectors most desirable and practical. Two such detectors, the CYGNUS experiment [1] and the CASA array [2], are operational in the western United States. These detectors use arrays of scintillation counters spreading out over areas of $\sim 10^5 \text{ m}^2$ to sample the air shower particles produced when energetic particles interact in the atmosphere. The measured particle density and arrival times are used to determine the energy and direction of the primary.

In recent searches for the Ultra High Energy (UHE, above 3×10^{13} eV.) sources, neither CYGNUS nor CASA has reported any significant evidence for continuous emission from any northern hemisphere source candidate. The lack of reported signal suggests that either sources such as CYG X-3 which were reported in the early 1980's, are no longer producing gamma rays or that the original observations were incorrect. The level of the upper limits placed on the flux from CYG X-3 are more than an order of magnitude below the flux reported by both Kiel [3] and Haverah Park [4]. The only reported observation of UHE emission was an episode in 1986, where the CYGNUS array reported a significant observation of showers from the direction of HER X-1 which showed both an anomalously high muon content for gamma induced showers and a period shifted from the reported x-ray period [5]. The same shifted period was reported in observations made within two months by both the Whipple [6] and Haleakala [7] groups. The significance of this observation (particularly the muon anomaly) requires further confirmation by simultaneous observations. CASA and CYGNUS now have this capability since they observe the same region of the sky at the same time.

The CYGNUS collaboration is proposing [8] a new water Čerenkov gamma ray observatory (MILAGRO) to cover the energy range above 1 TeV thus covering a largely unexplored

region of the spectrum. This detector would be located near Los Alamos in an existing pond at an elevation of 2650m. The air shower would be detected by 500 photomultiplier tubes spaced three meters apart, located one meter below the light-tight cover on the water's surface; 150 tubes near the bottom of the pond would be optically isolated from the top layer and would measure the muon content of the showers. The pond measures 60m by 80m at the water's surface and is about 8m deep. Simulations show that MILAGRO will trigger on a large number of events below 1 TeV and that its angular resolution will be significantly better than existing air shower arrays. This detector will observe, with 5σ significance, and in less than one year, the Crab signal reported by Whipple [9]. This detector has the advantages of an open aperture and 24 hour a day operation, making possible the search for episodic and known sources of TeV gamma rays.

The CYGNUS collaboration has also deployed five backyard-style swimming pools of radius 3.7 m (42 m^2 area) and depth 2.3m which are the enclosures for an array of water Čerenkov detectors. There is 2 m of water above the faces of the seven fast Burle PMTs ($< 2.5 \text{ ns}$ FWHM).

The pools are being run in coincidence with the CYGNUS air shower array; preliminary results on air-shower timing show that the angular resolution obtainable with these pools is substantially better than with the CYGNUS array alone. This will provide enhanced signal to background for the study of point sources.

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Rare Kaon decay Experiments at the Brookhaven National Lab

Collaborators: N.J. Hadley and Al Lee, IV at the the University of Maryland in Collaboration with Brookhaven National Laboratory, the Fermi National Laboratory, the Paul Scherrer Institute (formerly SIN), the University of Washington, and Yale University

Experiment 851 designed to study the decays $K^+ \rightarrow \pi^+ e^+ e^-$ and $\pi^0 \rightarrow e^+ e^-$ at the Brookhaven AGS finished data taking in the spring of 1989. This experiment was a continuation of Brookhaven experiment 777 which searched for the decay $K^+ \rightarrow \pi^+ \mu^+ e^-$ and set an upper limit on the branching ratio of 2.1×10^{-10} at the 90% confidence level [1]. The analysis of the $K^+ \rightarrow \pi^+ e^+ e^-$ data from Experiment 851 is now complete and has been published in PRL [2]. This decay has attracted considerable theoretical attention in recent years [3, 4] despite the observation of only 41 events of this type from one experiment [5]. The parameters that describe this decay are challenging to calculate and are dominated by long range hadronic effects. The decay $K^+ \rightarrow \pi^+ e^+ e^-$ can be used to predict the properties of the decay $K_L^0 \rightarrow \pi^0 e^+ e^-$ which is CP violating to lowest order and is now being searched for at CERN, FNAL, and BNL.

We obtained a sample of about 500 events and measured the branching ratio for $K_{\pi^+}^+$ to be $(2.75 \pm 0.23 \pm 0.13) \times 10^{-7}$ assuming a vector interaction with a form factor of $\lambda = 0.105 \pm 0.035 \pm 0.014$. We also found the branching ratio times decay probability for $K^+ \rightarrow \pi^+ X^0$; $X^0 \rightarrow e^+ e^-$ to be less than 1.5×10^{-8} (99% CL) over an X^0 invariant mass range from 150 to 340 MeV/c. This value for the branching ratio can be used to calculate in the model of reference [3] a limit for the branching ratio for $K_L^0 \rightarrow \pi^0 e^+ e^-$ to be less than 1.6×10^{-12} if the decay proceeds only through the CP violating piece of the $K^0 - \bar{K}^0$ mass matrix. This value is an order of magnitude smaller than the expected reach of proposed experiments looking for this decay [6].

Within the next year we hope to have results on the decay $\pi^0 \rightarrow e^+ e^-$.

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Hadron Spectroscopy and Structure

Investigator: D.C. Peaslee (visitor to the University of Maryland)

Hadron spectroscopy provides an excellent grounding in particle physics. As a glance at the reference volumes will show, it abounds in discoveries and problems resolvable by experiments that - although by no means trivial - do not match the monumental efforts required to breach frontiers at superhigh energies. Associated interpretations are mostly phenomenology, which aims - as in the historic case of atomic spectra - ultimately to deduce fundamental structure by amassing many correlated details of a system.

This relative accessibility makes hadron spectroscopy a specially suitable introduction to high energy physics research. The experiments are commensurate with individual PhD theses, as are the concepts with the physics background of graduate students. These advantages have been exploited in Europe and Japan, but have been largely overlooked in the U. S. physics community.

In an effort to help redress this imbalance and heighten local interest, an annual summer course in hadron spectroscopy has been instituted at the University of Maryland. Held for the last 4 years, the course has attracted a modest number of attendees, who have found it stimulating and useful to their research. There are 3 lecturers with enough overlapping interests to evoke significant discussion among themselves, from which the audience can learn much, especially by participation.

The lecturers are encouraged to write up their lectures for publication; the result is a volume, "Topics in Hadron Spectroscopy" by Nova publishers. The first volume is dated 1991, and a biennial sequence is anticipated.

The 4th Biennial Conference on Hadron Spectroscopy was held at the University of Maryland during August 12-16, 1991. Some 150 physicists attended, roughly half from the America and half from overseas. There were almost 150 talks, some speakers giving more than one; this made for a crowded program, but the participants were generous in appreciation. The talks are being published by World Scientific in Singapore, who received the manuscripts at the end of January; a volume of about 900 pages should be available shortly.

During the preceding week we also hosted the 4th Annual Summer Course on Hadron Spectroscopy with lecturers R. S. Longacre (BNL), H. W. Siebert (Heidelberg), and K. Takamatsu (KEK). The lectures from the 1st and 2nd courses have now been published by Nova Science (New York) under the title "Topics in Hadron Spectroscopy"; a copy is available for inspection.

Section D:
**The Solenoidal Detector Collaboration
at the SSCL**

In December of 1989 the University of Maryland HEP Group became one (of many) founding members of the Solenoidal Detector Collaboration. The collaboration is guided by an Executive Board, an Institutional Board, and a Technical Board (the names speak for themselves). Most of our faculty (A. Baden, A. Ball, C.Y. Chang, N.J. Hadley, A. Jawahery, S. Kunori, A. Skuja, and G.T. Zorn) are members of the collaboration, as is Prof. Jordan Goodman of the Maryland Cosmic Ray Group.

Our primary interest is the detection and measurement of muons and the design of the muon detector and trigger for the SDC. We have been concentrating on the design of the forward muon system (in the approximate pseudo-rapidity region of $1.5 < |\eta| < 2.5$ corresponding to azimuthal angles of 9.4° to 26.0°) and at present are responsible for the engineering design of the detector and detector support system in this rapidity region. A. Skuja has been leading the detector layout and design work and has spent the first six months of 1992 in residence at the SSCL. A. Ball, R. Bard, W. Miller and G.T. Zorn have developed a laser facility for testing various muon detector prototypes. These prototypes will also be tested at the Brookhaven AGS during May and June of 1992.

We have also participated in the development of a liquid argon (LAr) calorimeter adapted to the bunch structure of the SSC machine. A LAr calorimeter is no longer an option for the choice of calorimetry for the SDC. However, measurements last year at BNL in a 20 GeV pion beam confirmed that many of the problems associated with long signal collection times of LAr can be solved. The Maryland group instrumented the beam line and provided the DAQ for the BNL tests. N.J. Hadley has led our LAr effort with able assistance from D. Fong and J. Goodman. Prof. Hadley presented the first results of the test beam work at the 1991 Vancouver DPF meeting.

We have received continuing R & D support through the SSCL: \$45,000 in 1990, \$ 160,000 in 1991, and \$ 150,000 in 1992 as supplements to our D.O.E. contract or grant. We have no Texas Commission money for SSC R & D.

D. Baden and S. Kunori have done extensive work on SDC computing. Prof. Baden serves on the SDC technical board as a member responsible for planning the online and offline computer architecture for the experiment. Prof. Baden is sharing a DOE grant awarded under the Presidential High performance Computing and Communications Initiative for his work. He has been awarded an SSC fellowship, as well. Dr. Kunori has been organizing the detector simulation environment (the so-called Monte Carlo SHELL) as well as overseeing the detailed muon detector simulation group.

The Design of the Forward Muon System for SDC and the R & D of High Resolution Muon Chambers

Investigators: A. Ball, N.J. Hadley, S. Kunori, A. Skuja, G.T. Zorn at the University of Maryland in collaboration with Arizona, Argonne, Brandeis, Colorado, Fermilab, Harvard, Illinois, KEK, Michigan, Minnesota, Osaka City, Rochester, Tsukuba, Tufts, Washington, Wisconsin.

I. The SDC Muon System

The basic layout of the SDC detector and muon subsystem is shown in Fig. 45. The central (barrel) and intermediate (transition) muon regions ($|\eta| < 1.5$), consists of three superlayers of muon chambers, one inside and two outside a 1.5 m thick octagonal magnetized iron toroid ($B \approx 1.8T$), all located outside of the central calorimeter. Within each superlayer, the majority of wire planes are arranged in such a manner that the wires form projective roads to facilitate the implementation of a simple wire trigger that makes a local measurement of the azimuthal angle (θ).

The forward muon detector consists of 2 superlayers of wire chambers, both upstream and downstream of a 3m octagonal magnetized iron toroid. The layers are placed 1.2m apart upstream of the forward toroid and 4m apart downstream. The toroid itself is split into 1.5m sections allowing the possibility of an additional superlayer of chambers placed between them as an upgrade. This layout of chambers allows the measurement of the muon trajectory both before and after the toroidal magnet, so that a stand alone measurement of the muon momentum is possible. The superlayer buried inside the toroid allows one to distinguish large angle scatters in the toroids by low energy muons that fake high p_t events. Once a scatter has been identified, this layer is then necessary for the reconstruction of the correct muon momentum. Space is left for a set of gas Cherenkov counters between the final two superlayers of the forward muon system to allow the rejection of low energy backgrounds while forming the muon trigger.

Two planes of scintillator are placed behind each of the outer two superlayers of wire chambers in the forward region. These scintillators tag the correct beam crossing and also indicate the in-time particle road for the muon trigger and reconstruction.

The drift tubes that form the muon detector are approximately 9 cm. in radius (4.5 cm maximum drift) in the barrel region, while they are only 4.2 to 5.7 cm in radius to allow for higher occupancy in the forward region. While the design of the tubes has been chosen for the barrel, the exact configuration of the forward region drift tubes will be chosen after detailed beam tests this summer. However, the SDC base line design calls for similar round tubes in the forward region as in the barrel (if possible).

The muon detection system has five distinct goals, each of which puts different requirements on the design of the system. These five goals are the following:

Figure 45: The SDC Detector (March, 1992)

1. To provide a Level 1 trigger;
2. To provide information for the Level 2 and Level 3 triggers;
3. To identify muons;
4. To improve the momentum resolution at very high muon transverse momenta;
5. To provide the capability of operation at luminosities above the design level.

Level 1 trigger

The Level 1 trigger operates at the beam crossing rate of 60 MHz and must arrive at a decision in 2 μ s. Thus it must be simple and fast, and still have the ability to reduce the accepted rate to a few tens of kHz. It is possible to do this with the muon system by triggering on a coincidence between the scintillator layer(s) and a wire chamber trigger that is derived locally within one of the superlayers beyond the toroids.

The wire chamber trigger, which is in coincidence with the scintillator trigger, is similar to that used by CDF. The wires in every other plane are projective to the interaction point. The time difference Δt between pulse arrivals on paired wires is then inversely proportional to the transverse momentum of the trajectory. A trigger threshold can be set on Δt by a simple circuit, whose deadtime is matched to the pulse pair resolution of the chambers. To avoid inefficiencies due to soft particles accompanying a high-momentum muon, a logical OR of triggers from the last two superlayers is employed. The wire chamber trigger has an adjustable threshold.

For transverse momentum trigger thresholds of interest at Level 1, namely 10–40 GeV/c, the resolution of the trigger is dominated by multiple Coulomb scattering in the calorimeter and toroids, and has an rms value of about 25%.

Level 2 and Level 3 triggers

The purpose of the Level 2 trigger is to reduce the trigger rate by sharpening the transverse momentum resolution. This is done by connecting a θ measurement in the muon system with a track-stub measurement in the inner tracker. In the absence of scattering, all valid trajectories beyond the flux return point to the interaction point in θ . By using projective θ wires, the simple circuit discussed above for the Level 1 trigger can be employed to find stiff tracks (*i.e.*, those that have not scattered more than expected) and to record the θ information for transmittal to the second-level trigger processor, where a match is made to the inner tracker information. At Level 2, a coincidence of detector octants containing a Level 1 θ trigger and a Level 2 θ trigger should be sufficient.

At the highest values of $|\eta|$, the Level 2 θ trigger is replaced by an angle-angle measurement in θ across the 4 m thick iron toroids. For this reason, an additional superlayer of θ planes is employed in the forward angle region.

The function of the Level 3 trigger is to insure that the lower-level triggers were valid and that they match. Stereo information is used in this process. At forward angles, stereo information is generated by simply rotating planes of θ wires by 15 and 30 degrees.

Identification of muons and Momentum Measurement

The key to muon identification is the redundant momentum measurement based on the toroids. These measurements are multiple-scattering-limited at 18% in the central region and 11% in the forward region. They are accomplished by angle-angle measurements in θ across the toroids. No chambers beyond those required for the second-level trigger are required in the forward region.

We believe that the proposed muon detector has enough resolution and redundancy to be capable of operation well above the design value of $10^{33} \text{ cm}^{-2}\text{s}^{-1}$. At ten times design luminosity, we estimate that the rate of single hits per unit of pseudorapidity in the first layer of the muon system varies from about 1 MHz at $\eta = 0$ to 100 MHz at $\eta = 2.5$. This latter value corresponds to a 300 kHz rate in a 4 cm drift chamber cell, or an occupancy of 12% in the 400 ns time window set by the maximum drift time. The occupancies of cells at $\eta = 0$ will be about a factor of 50 less, indicating that the muon system will remain operational at very high luminosities.

II. Research and Development Work at Maryland

A. Ball, R. Bard, J. Cohen, J. Colmer, F. Desrosier, D. Fong, M. Garza, N. Hadley, J. Hershey, W. Miller, M. Murbach, L. Schaffer, A. Skuja, G. Zorn at the University of Maryland

The Maryland Group is working on the design of the muon detector in the forward region for the SDC. The muon detector at forward rapidities ($1.5 < |\eta| < 2.5$) has to provide an adequate measurement of the muon trajectories for both the muon trigger as well as a good momentum determination in a region where the central tracker no longer has adequate coverage. The muon detector consists of four measuring stations, two before a 3m iron toroid and two after it. To achieve the momentum precision desired in this region, each measuring station must measure the relevant coordinates to 150 microns. This resolution is more than adequate for the trigger. The number of detector planes in each of the stations is just adequate to do the required measurement. A fifth station is placed in the middle of the magnetized toroids to identify large angle scatters of energetic muons. The required precision and lack of redundancy imply that the 150 micron resolution per station translates to about 250 micron resolution per cell in the detector.

The muon detectors will be of the drift tube type ("closed geometry") arranged in an octagonal geometry. Tube type chambers have been chosen to restrict cross-talk and to prevent broken wires from introducing large gaps in the acceptance. Because of the large muon rate in this region for the expected luminosities, as well as possible backgrounds from soft neutrons, the cell size of the tubes has been chosen to be 4.2cm to 5.7cm in radius, ranging in length from 1.2m to about 8m.

We have designed and built several drift cells and established a test facility based around a NIKHEF type 1A nitrogen laser and associated optical bench. This device can produce locally focussed ionization, or extended tracks, in the drift cell gas at precise locations. The drift cells are fitted with conductive cathode windows which are transparent to the laser light but maintain the electrostatic field.

A VAX-based data acquisition and monitoring facility has been developed from a Fermilab system to meet the requirements of this laser facility and future test beam or cosmic ray work. Simple data analysis and graphical presentation is handled by a dedicated work station with appropriate software, which forms part of the equipment obtained for the facility. The work on the facility was carried out by A. Ball, R. Bard, J. Colner, D. Fong, W. Miller, and G. Zorn.

Sub-100 μ m resolution has been obtained elsewhere in real systems of ~ 1 cm square aluminum drift tubes, operating in limited streamer mode. Such results have been duplicated at Maryland, but the isobutane-rich gas mixtures, needed for streamer mode, are ruled out for SDC on safety grounds.

In the design of high resolution drift cells, particular attention must be paid to the internal electrostatic field distribution, since the avalanche gain, electron drift velocity and high voltage stability are crucial parameters. A vital ingredient in the design process has been the use of simulation programs, such as CERN's GARFIELD package, to predict the potential, field and isochrone maps for various electrode configuration. This has significantly reduced the time required to produce viable prototypes. Most of the GARFIELD calculations have been carried out by J. Cohen.

To enable us to develop cells which operate in proportional mode, we have evaluated high gain, very fast charge amplifiers designed by Harvard, Lecroy and our own electronics group. The Lecroy design has been provisionally selected on cost benefit grounds. Using this amplifier, we have confirmed that square aluminum drift tubes can give sub-100 μ m resolution of laser tracks when operated in proportional mode with 90% argon, 10% ethane gas mixtures. Reasonable two-track resolution (~ 5 mm) has also been demonstrated using primary and reflected laser beams to generate the two tracks. Attempts to reproduce these results using argon/carbon dioxide gas mixtures have been thwarted by the well known poor high voltage stability of CO₂ quenched mixtures, which also require very high drift voltages for approximate saturation of the electron drift velocity.

Trigger requirements and structural simplicity strongly favor the development of a rectangular drift cell. In this case, some form of field-shaping is required, without introducing great complexity. Very simple field-shaping rectangular cells, with cylindrical or flat electrodes at approximately anode voltage shielding the anode from the long sides of the cells, have been designed, built and tested. The very encouraging time-distance linearity and resolution of these prototypes, with argon-ethane gas mixtures, suggest that 4cm $\times$ 6cm cells of this type may satisfy the requirements of the forward muon system. Fig. 46 shows typical drift times vs distance and resolution vs distance relationships.

WDC2-d, 50micron, +2.15kv, A/E:90.1/9.9, TDC
 TRA402 gain=100, 62mm lens, 4/27/92

Figure 46: Drift time vs distance for a square drift tube cell as measured by the laser facility

During 1992, we will conduct extensive test beam measurements at Brookhaven National Lab with help from collaborators in SDC. These will measure the properties of several drift cell design options, including those previously tested at Maryland using laser beams, as well as the design chosen for the SDC barrel muon detector (where the resolution requirements are less stringent).

The overall resolution constraints result in a very strong linkage between the drift cell design and that of the support structure. Any viable solution relies heavily on the cathode tubes as structural elements. In a very crowded environment, front end electronic design and maintenance requirements also strongly affect the overall design criteria. System integration issues suggest that the best focus for development of an integrated design would be the construction this year of a complete octant section, although shortfalls in manpower and funding and uncertainty in the choice of cell design make this a considerable challenge.

The mechanical design of the Forward Muon System stations requires that the drift tubes be assembled into octant modules which are mounted on a super-module frame. The even and odd octants are displaced along the beam direction to allow for an overlapping structure, thus exhibiting no phi cracks. We are in the process of designing the super module frame, its kinematic support located in the top third of the inside diameter, and the interconnecting support to the FMS infrastructure. This is a stabilized design because the center of gravity of the super module is below the supports. The kinematic supports are remotely controlled retractable cylinders. The corresponding locating receptacles on the FMS infrastructure are surveyed into position and secured. The finite element model needed to analyze the super module structures to determine the size of the structural members and the corresponding stress and deflections will be developed.

The octant modules will be designed as a glued together honeycomb structure, with the drift tubes representing the honeycomb, and the end plates, cover, and internally layered sheet stock representing the webbed structure. An investigation will be made to determine if each octant can be manufactured into one solid structure, then assembled into the super module frame, or if smaller sections of the octants can be constructed and then assembled into the frame. Each of the octants (or pieces) must be precisely located by surveying and adjusting until the octants have a fixed, known position on the super module and relative to the IP. In the final analysis the wire to wire location must be electrically known to 150 microns in the radial direction.

A full size prototype octant will be constructed to determine the manufacturing technique and required part tolerances.

The manufactured octant then will be installed onto a test fixture that will be designed and constructed at the University of Maryland to allow measurement of the deflection of the composite structure and the location of the wires in different rotational positions.

The Maryland Group will also interact with the engineering design groups in the collaboration and at the SSCL to ensure that the designed support structures and connections will

provide the required local and global resolution. The engineering design work at Maryland has been carried out by mechanical design engineers F. Desrosier and M. Murbach assisted by engineering students M. Garza and J. Hershey.

III. Simulation of the SDC Muon System

S. Kunori at the University of Maryland in collaboration with physicists at Colorado, IHEP (Protvino), Illinois (Champaign-Urbana), and Northern Illinois

The main purpose of simulation at this stage of the experiment is to provide informations for detector design and to verify that the design satisfies various requirements for the detector. The forward muon system has five distinct requirements: (a) to provide a Level 1 trigger; (b) to provide information for the Level 2 and Level 3 triggers; (c) to identify muons; (d) to improve the momentum resolution at very high energy; and (e) to provide the capacity of operation at luminosity above the design level. In order to test designs against these requirements, various software programs have been developed. We describe some of results from those programs.

Chamber layout for Level 1 trigger

The rate of muons in the muon detector has been calculated by Dr. Hedin at Northern Illinois University using the event generator, ISAJET with a simple simulator for hadron punchthrough and decay in flight in the detector. Combined rates for prompt, punchthrough and decay muons are shown in Fig. 47 as a function of transverse momentum (p_t) at the calorimeter depth, 24λ . The rate at $p_t = 10 \text{ GeV}/c$ is about 1000 Hz which is about the desired rate for the Level 1 output from the muon system.

The Level 1 trigger will be formed by signals from scintillation counter planes (FS4 and FS5) (or Cherenkov counters (FCC)) and wire chambers (FW4 and FW5) behind the toroidal magnets. The counters in FS4 and FS5 are segmented in such a way that they form coarse roads pointing to the interaction point (IP). They give an approximate p_t threshold for muons and produce a time reference for FW4 and FW5. An optional FCC also may provide the p_t threshold and beam crossing time reference. The wire chamber trigger from FW4 and FW5 provides an adjustable p_t threshold in the Level 1 trigger. Wires in a pair of theta planes (bend view plane) are aligned to form projective geometrical roads, so that a difference of two drift times is proportional to a bend angle in the forward toroidal magnets.

An optimization of chamber layout for the Forward Muon System for the Level 1 trigger and its acceptance were studied by Dr. Kunori using a full detector simulation program SDCSIM which has been developed by a group headed by him and widely used in SDC. More details about the program were described in the 1991 progress report.

The trigger efficiencies as a function of p_t are shown in Fig. 48 for a specific value of the p_t threshold of $15 \text{ GeV}/c$. The efficiencies shown in 48(a) and (b) are for triggers formed locally at FW4 and FW5, respectively; while (c) is for the case of a simple coincidence of the FW4

Figure 47: Combined Rates for prompt, punchthrough and decay muons

and FW5 triggers. The efficiency approaches 100% at about 20GeV/c and the coincidence removes many events in the low energy tail of the efficiency curve. The additional triggers due to electromagnetic debris accompanying the muon track are shown in black. No big increase in the trigger rate is seen due to this debris.

His study also showed that: (a) the distance between lateral wires should be at least 5cm to contain $p_t = 10\text{GeV}/c$ muons in a road determined by a pair of drift tubes; and (b) 1mm misalignment between two theta planes for the pair does not degrade the trigger efficiency for p_t thresholds below 50GeV/c.

Beam pipe and absorbers

The major background for the forward muons system is generated by particle interactions in the material surrounding the beam pipe. Dr. Kulik of IHEP, Protvino has been studying designs of the beam pipe, a forward absorber, and a rear absorber. The former protects FW1 and FW2, while the latter protects the low beta quadrupole magnets as well as FW4 and FW5. His study indicates that:

- Changing the shape of the beam pipe from a cylindrical tube to one conical in shape pointing to the IP reduces the background rate by a factor of 20.
- The forward absorber must have a minimum thickness of 30cm to protect FW1 and FW2.
- A large neutron flux is produced in the quadrupole region. These neutrons contribute to a background of uncorrelated hits in FW4 and FW5. To absorb these neutrons, an iron absorber 1.5 meters in radius, is required, if the quadrupole magnets is place at 20meters from the IP.
- The neutron background in this region becomes negligible, if the magnet is moved from 20 meters to 36 meters from the IP. In this case, the conical shape beam pipe helps to reduce backgrounds further by a factor 10.

Pattern Recognition

The pattern recognition for muon tracks is a major issue. A program is under development within the SDCSIM framework by Dr. Kunori. First results from the program are expected to be available by the end of April, 1992.

Figure 48: Combined Rates for prompt, punchthrough and decay muons

Research and Development of A Liquid Argon Calorimeter for the SSC

R. Black, C.Y. Chang, H. Deng, D. Fong, N. Hadley, and G. Long at the University of Maryland in collaboration with the Brookhaven National Lab, The University of Rochester, the Lawrence Berkeley Lab, the Superconducting Super Collider Lab, the Oak Ridge National Lab, the University of Tennessee, the University of Mississippi, the University of Washington, Florida State University, Michigan State University, and Adelphi University.

We are members of the Liquid Argon Calorimeter Collaboration (LACC) for SSC Research and Development. This proposal was first funded in FY 1990 with part of the funds coming from the DOE HEP and part from DOE SSC. Maryland's portion of the 1990 funding was \$45,000, and of the 1991 funding \$65,000. The LACC has built a prototype lead liquid argon calorimeter. The calorimeter has lead plates since we believe that uranium, which has been successfully used by the DØ experiment at FNAL and by the Helios experiment at CERN, will be too expensive for use at the SSC. A unit cell of the calorimeter consists of one 12 mm lead plate followed by a 2mm argon gap, followed by a 1.6 mm G10 printed circuit board and then another 2 mm argon gap. The calorimeter has been tested in a test beam at BNL. The purpose of these tests is to measure " e/π " as a function of momentum and to test response uniformity across the gaps between modules.

The Maryland members of the Liquid Argon Calorimeter Collaboration (LACC) include Professors Hadley, Goodman, Chang, and Baden and Research Scientist Doug Fong plus three students. Maryland was responsible for providing instrumentation for the test beam. This instrumentation included Cerenkov counters for particle identification as well as a scintillating fiber hodoscope for triggering and beam definition. We were also responsible for the data acquisition system.

We completed the revamping of two Cerenkov counters in early 1991 and helped to install them in the beamline at BNL. We increased the length of the Cerenkov radiator to 3 meters and built new windows for both counters. These Cerenkov counters have now been successfully used to obtain well identified pion and electron beams at BNL at momenta from 500 MeV/c to 20 GeV/c. In addition, we built a 48 mm by 24 mm scintillating fiber hodoscope for the test beam out of 1 mm square scintillating fibers. This hodoscope, which is readout by 40 1/2" phototubes, enables us to measure the position of particles in the beam as well as to study the effects of high rate ($> 2 \times 10^7$ particles per second) data taking. The outputs of the 40 phototubes go to TDC's which record a time history for each event. The time resolution of the individual fibers was measured to be about 1.8 ns RMS, and their efficiency to be $92 \pm 2\%$.

We setup the data acquisition system for the testbeam using a VAXStation and CAMAC. We modified a Fermilab data acquisition program so that it was compatible with LACC needs in the BNL testbeam. Both the hardware and software were ready in time for beam data taking at BNL which began in April 1991.

Results from the LACC work were presented by Prof. Hadley at the Vancouver DPF meeting in August 1991.

SDC Computing and Software Design

D. Baden and S. Kunori have done extensive work on SDC computing. Prof. Baden serves on the SDC technical board as a member responsible for planning the online and offline computer architecture for the experiment. Prof. Baden is sharing a DOE grant awarded under the Presidential High performance Computing and Communications Initiative for his work. Dr. Kunori has been organizing the detector simulation environment (the so-called Monte Carlo SHELL) as well as overseeing the detailed muon detector simulation group.

Technical Proposal

Professor Baden, as a member of the SDC Technical Board, is co-leader (with Larry Price from ANL and Irwin Gaines from FNAL) of the steering committee charged with completing the design and costing for the SDC computing system. The report is finished, and has been presented to the SSCL Program Advisory Committee (PAC) for review.

The major computing challenge for SDC arises from the large quantities of data that must be dealt with at each stage of processing. The upper limits of a 100 Hz trigger rate and a 1MB event size requires a system sized for raw data sets or up to 10^{15} bytes per SSC year. From CDF experience, production reconstruction will create a roughly equal quantity of computed data, requiring total storage capacity of 2×10^{15} bytes per SSC year. Dealing with this large quantity of data (not just storage, but also providing access) drives the planning of the computing system much more than the production processing requirement, estimated at 10^5 "SSCUPS", a measure developed by the SSC Laboratory equivalent roughly to the performance of a VAX 11/780 on typical physics codes.

The hardware to process this data will include a major facility for SDC production reconstruction located at SSC Laboratory. It will make use of processors that, for cost effectiveness, will probably be chosen from the commercial RISC offerings available later in the decade. Storage volumes are expected to be housed at least partly in an automated system to reduce manual mounting. We estimate the number of volumes it will take to provide storage for and access to 1000s of Terabytes per year in 1999 by using 19 mm helical scan tapes (DD2) with a storage capacity of approximately 100 GByte/reel. We would require of order 10^4 of these volumes. Note that at this time there is no commercially available storage robot/silo for this technology. As for data access, in present (1992) thinking, the output of the production reconstruction will be divided up into physics oriented data sets, from which physicists will primarily draw samples of data for analysis. We believe that the data management requirements for this mode of access will be extremely challenging. With continuing R&D support we will be pursuing more effective and efficient methods of data organization and management.

Early in the analysis chain, but probably following production reconstruction, the data, (or a description of the data) will be put into a database format to facilitate both searching for events matching physics criteria and access to the particular parts of event data required

for a given analysis. The ability to design a database with the needed capabilities can be inferred from present operational and developmental database systems, but working with the computing industry and academic community to be sure that SDC needs are met will require a commitment to R&D by the collaboration and the SSC Laboratory.

Separate computing systems which emphasize interactive capabilities will be needed for later stages of analysis, including selection of events and histogramming or other methods of presentation. Extensive analysis must be made of the methods of distributing processed data and providing access for physicists doing analysis. It is likely that an efficient balance of the use of networks and of mechanical movement of data on tapes or other storage media will be achieved with the provision of a number of regional centers for SDC computing. The regional centers would be located within the US and in Japan, Europe, and other foreign centers, at geographically convenient points to provide access to (at least) intermediate size data samples.

Finally, we assume that the individual workstation, strongly coupled to a distributed system, will be the standard desktop device that a physicist uses when doing analysis, both for local processing and for access to computing facilities at regional centers or at the SSC laboratory.

Software for SDC offline computing is expected to be divided into two broad categories. The first will be a "kernel" that provides a structure for SDC software and the general services needed by all parts of the system. The kernel will be the responsibility of an SDC Computing Group consisting of computing professionals located predominantly at the SSC Laboratory. The second category of software is made up of the parts that relate specifically to the various pieces of the SDC detector. These parts will be provided by the appropriate subsystem groups. The Computing Group will not write the detector-oriented code, but will provide development systems and tools, will define standards for the software, and will organize code management and distribution. The computing group will also provide for review processes by which completed software becomes part of the SDC production system. Software engineering methods are expected to be used throughout SDC software development, but with more rigor in the kernel development than in the detector-oriented software.

SDC will necessarily rely on commercial software to the extent possible. Standards defined by the computing industry will be relied on heavily to allow replacement and upgrading of software with new versions, either commercial or written by SDC. The extended time scale for SDC, both before and after turnon, dictates the maximum possible use of standards to minimize obsolescence.

The strategy outlined above requires development of most of the kernel system before the subsystem groups begin writing the detector software. Thus work on the kernel must begin essentially at the same time as the construction of the hardware components of SDC, at the beginning of FY1993. Development of the first release of the kernel system requires roughly two years, after which work on subsystem software begins. Initial versions of all

SDC production code should be complete by the end of FY1998, to allow systematic review and testing to ensure a capable production software system for the beginning of data taking.

Initial estimates of resources needed for computing are \$24M for purchased systems and software, and 120 FTE-years of effort for work done by computer professionals for SDC. In addition, a large amount of effort will be invested by physicists in the detector subsystem groups to write those parts of the code.

HPCCI Database Proposal

Data from detectors at the Superconducting SuperCollider (SSC) will strain existing approaches to data storage and access even more than the availability of computing power to process the data. At least part of the required increase of about 10^4 in data handling must be provided by improved algorithms and not just by improvements in storage devices. A move to a database organization for data from an SSC detector would allow reading only those parts of events which are of interest for the particular analysis, effecting a substantial saving in data handling and I/O bandwidth requirements. Professor Baden is a co-founder of a collaboration which has submitted a proposal to the DOE Office of Scientific Computing Staff under the High Performance Computing and Communication Initiative to research and develop alternative ways of managing and accessing large amounts of scientific data. As part of an early start funding, the group is working on an R&D proof-of-concept which would entail an evaluation of a database organization scheme in high energy physics (HEP). Our goal is to understand if such a scheme is feasible in the existing HEP environment, and perform an evaluation of how such a scheme may scale to meet SSC requirements. We propose to continue this R&D in order to fully develop an object oriented or relational database system for SSC data, and detail a suitable 5 year plan for such an effort.

SDC Shell

Since the SDC detector will be very complex and many people are working on various subdetector systems, it was realized that we needed a well coordinated effort to establish a complete system of programs for Monte Carlo code, event reconstruction code and analysis code.

Based on his experience in software development for DØ and E665 at Fermilab, Dr. Kunori proposed a simple system of programs to the SDC collaboration during the summer of 1990. The proposal was accepted. The collaboration formed a programming group and asked him to lead this effort.

The requirements for the system were as follows:

- The program should be able to run on any computer commonly available in the high energy physics world, now and in the future.

- The framework program should have minimum functionality: basic i/o capability, data management, machine independent file access and error handling.
- Any program package should be written in modular style and be able to run under the common framework.
- The software system should be easily distributed to institutions in the collaboration.

After several months of design work of the program system, actual coding started in November, 1990. Dr. Kunori was mainly responsible for the writing of the framework program, while Y.Takaiwa of KEK wrote an interface program to the event generators, ISAJET, HERWIG and PYTHIA. D.Coupal of SSCL added a single particle generator to the interface program. For detector simulation, we have adopted GEANT. An interface program between GEANT and each subdetector code was written by D.Adams of Rice.

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and
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