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Experimental Studies of Elementary Particle Interactions at High Energies

Summary Technical Progress Report
Contract DE-AC02-~~97~~ER40325

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Abstract

This is a report of the research activities of the Experimental High Energy Physics group of The Rockefeller University. It covers the time period from February 1, 1987 to the present, during which the group has been receiving support from the Department of Energy (DOE) under contract DE-AC02-87ER40325. As this is an annual progress report, the emphasis is on last year's research activities. However, since it is the last of a series of 5 such reports to be submitted to the DOE under the present 5 year contract, an effort has been made to provide comprehensive coverage of the research activities of the group throughout the contract period.

In the past 5 years, our research program encompassed three major areas: the UA-6 experiment at CERN, the CDF experiment at Fermilab, and several SSC projects.

The UA-6 experiment studies direct- γ and J/Ψ production in pp and $\bar{p}p$ interactions at $\sqrt{s} = 22.5$ GeV. It is a fixed target experiment using a hydrogen gas-jet target with either the stored proton or antiproton beam at the CERN SPS collider. Since the direct- γ cross sections are characteristically dependent on the poorly known gluon structure function of the nucleon, while the difference between the pp and $\bar{p}p$ cross sections is independent of the gluon and depends on the strong interaction coupling constant Λ_{QCD} , measurement of these two cross sections provides information on both the gluon structure function and Λ_{QCD} . Being a high luminosity fixed target experiment, UA-6 can probe a higher $x_T (= 2p_T/\sqrt{s})$ region than is accessible to other collider experiments, and the ability to measure pp and $\bar{p}p$ production in the same detector reduces systematic uncertainties.

In the CDF experiment we have concentrated in the area of "small angle physics", where our objective has been to measure the elastic, diffractive and total cross sections, and to provide an absolute calibration of the machine luminosity. In collaboration with two other groups of CDF, we built forward spectrometers employing the machine magnets themselves and detectors in "Roman pots". We collected data during the 1988-89 collider run, and we have been analyzing these data since the end of the run. The detectors in the Roman pots consisted of drift chambers, silicon strip detectors, and scintillation counters for triggering. The drift chambers, the

scintillation counters, and the electronics for both chambers and silicon were designed and built at Rockefeller. Our group has made an absolute measurement of the machine luminosity, as described in last year's progress report, and has obtained a value for the total cross section at $\sqrt{s} = 1800$ GeV.

As the small angle data analysis is coming to a conclusion, our interest has shifted towards other CDF projects. In the last year, we have become heavily involved in the plug calorimeter upgrade program. Our main contribution has been the design and construction of a fiber-splicing machine, which is currently being used to splice wave-length shifting to clear fibers for the plug calorimeter prototype. We have also taken responsibility for the preparation of the photomultiplier assemblies for the prototype (phototubes, bases, and mechanical assembly design). In addition to the plug upgrade, we have designed and made a full-scale model of a tile/fiber "Microplug" calorimeter intended to cover the presently uninstrumented region of polar angles $0.5 < \theta < 2^\circ$. A proposal to build and install a Microplug for the next collider run is being submitted to the collaboration.

Our SSC R&D projects are related to two experiments: the "Solenoidal Detector Collaboration" (SDC) and the "Low p_T Physics" experiment (EOI-2). In connection with SDC, we are involved in three different projects: Preshower/Shower-Maximum detectors, high pressure gas calorimetry, and scintillator tile/fiber calorimetry. The first two are discussed in detail in the SSC section of this report; our work on the tile/fiber project coincides with that in the CDF plug upgrade program and is discussed in the Fermilab section. The EOI-2 is a proposal to measure the elastic, diffractive and total cross sections at the SSC. For this experiment, we have undertaken the development of a system of fast readout of scintillating fiber detectors using silicon drift chambers.

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October 1990
- [2] "Letter of Intent: Solenoidal Detector Collaboration"
SDC-90-00151
November 1990 (approved)
- [3] "Low p_T Physics at the SSC"
EOI-2
May 1990
- [4] "Subsystem Proposal for Pre-Shower and Shower-Maximum Detectors"
Submitted to the SSC
September 1990 (approved)
- [5] "Proposal for the Development of High Pressure Gas Calorimetry for SSC"
Submitted to the Texas National Research Laboratory Commission
October 1990 (approved)
- [6] "Development of a Compensating Scintillator Plate Calorimeter System for the SSC"
Proposal submitted to the SSC
September 1990 (approved)
- [7] "Fast Readout of Scintillating Fiber Detectors Using Silicon Drift Chambers"
Proposal submitted to the SSC
October 1990 (approved)

ROCKEFELLER UNIVERSITY
Experimental High Energy Physics

Responsibilities of physicists
on projects described in this report

June 1, 1991

<u>Name</u>	<u>Position</u>	<u>UA6</u>	<u>CDF</u>	<u>Tiles</u> ^[1]	<u>Preshower</u> ^[2]	<u>Silicon</u> ^[3]	<u>Gas</u> ^[4]
K. Goulianos	P		XX	X			
R. Rusack	AP				XX		
S. White BNL	AP		X	XX			
G. Apollinari	aP		X	X			
P. Cox	aP	XX					
N. Giokaris	aP		X	X			XX
P. Melese	aP				X		
A. Vacchi Trieste	aP	X				XX	
T. Chapin Gone	SRA		X				
P. Giacomelli	PD	X				X	

Delphi

Wang from Harvard post doc (Strauss)

Titov from Dubna student

Mohr ~~Postdoc~~ **Postdoc**

XX

Project Spokesperson for Rockefeller

Demois **live**

~~Postdoc~~ **Postdoc** Brandeis

Wu **Postdoc** Yale (Sandhu)

Bhatti **Postdoc** Washington (Lubatti)

Magharian Student (not present)

2 Students

SSC Projects

- [1] Development of a Compensating Scintillator Plate Calorimeter System for the SSC
- [2] Subsystem Proposal For Pre-Shower and Shower-Maximum Detectors
- [3] Fast Readout of Scintillating Fiber Detectors Using Silicon Drift Chambers.
- [4] Proposal for the Development of High Pressure Sampling Gas Ionization Calorimetry for the SSC

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1 CERN: The UA-6 Experiment

1.1 Introduction

Experiment UA6 was proposed in 1980, took its first data in Fall 1984, and completed its final data-taking at Christmas 1990, running until the demise of the CERN SPS Collider itself. Initially conceived as an experiment to study e^+e^- , γ , π^0 , and hyperon production in antiproton-proton reactions at $\sqrt{s} = 22.5$ GeV, as well as low- t elastic scattering in both $\bar{p}p$ and pp , it has gradually focussed on direct- γ and J/Ψ production. The elastic scattering experiments were successfully completed without the need for the large accumulated luminosity required to reach high p_T 's in direct- γ production. Hyperons have proved much harder to trigger on than expected in the unshielded Collider environment, and it was only during the last run (Fall 1990) that a sufficiently sophisticated trigger was devised that could select Λ hyperons. This involved a network of Transputers interfaced to the MWPC electronics which performed parallel data acquisition and track reconstruction in order to search for the characteristic "vee" of two charged tracks appearing from a vertex downstream of the target. This system was not fully-debugged by the end of the run, but the experience gained with such a network is of considerable importance for future high-energy projects.

1.2 The experiment and its aims

UA6 is a fixed-target experiment using a hydrogen gas-jet target with either the stored proton or antiproton beam of the CERN SPS when in collider mode. The detector is a double-arm magnetic spectrometer, one arm above and the other below the SPS beam pipe, each arm instrumented with MWPC's and a lead/proportional-tube gas electromagnetic calorimeter. The chambers detected charged particles, the calorimeter photons and electrons. The calorimeter used horizontal and vertical planes of 1 cm width proportional tubes, well-matched to resolving the daughter γ s from a 100 GeV π^0 decay which have a minimum separation of 2.7 cm. By assembling the detector in either of two orientations in the SPS tunnel we could view either proton-hydrogen (pp) or antiproton-hydrogen ($\bar{p}p$) collisions at $\sqrt{s} = 24.3$ GeV (the Collider beam momenta were typically 315 GeV/c). The attraction of direct- γ physics has been its relative simplicity in theoretical terms, since the γ is expected to be produced directly at one vertex of a parton-parton interaction, and to emerge without the confusion of fragmentation common to hadron production. Full next-to-leading order calculations of the direct- γ production cross-section within QCD now exist, and are characteristically dependent on the poorly-known gluon structure function of the nucleon. The difference between the $\bar{p}p$ and pp cross-sections, however, is independent of the gluon, but depends on the strong-interaction coupling constant Λ_{QCD} . Hence measurement of these two cross-sections provides information on both the gluon structure function and Λ_{QCD} .

Being a fixed-target experiment allows UA6 to probe a higher $x_T (= 2p_T/\sqrt{s})$ region than is accessible to other collider experiments, and the ability to measure $\bar{p}p$ and pp production in the same detector reduces the contribution of many systematic effects.

1.3 Data collection

UA6 had running periods (typically of duration 3–4 months) within each of the years 1984–1990. The type of data and accumulated luminosity on tape breaks down as follows:

<i>year</i>	<i>type</i>	<i>luminosity</i>	<i>trigger</i>	<i>comments</i>
1984	$\bar{p}p$	40 nb^{-1}	hodoscope	only 10% full jet-density
1985	$\bar{p}p$	0.5 pb^{-1}	processor	
1986	pp	40 nb^{-1}	hodoscope	match 1984 data
		1.5 pb^{-1}	processor	
1987	pp	0.5 pb^{-1}	processor	ACOL start; upgraded expt
1988	pp	3.0 pb^{-1}	processor	
1989	$\bar{p}p$	3.5 pb^{-1}	processor	
1990	$\bar{p}p$	4.0 pb^{-1}	scintillator tiles	

No more data on direct-photon production in $\bar{p}p$ collisions at fixed-target energies are expected to be collected again, anywhere; our data dominate the world sample.

During the history of UA6 we progressively upgraded the detector. A major upgrade was performed before the 1987 run (necessitating an addendum to our proposal), which also marked the debut of the the CERN Antiproton Collector (ACOL) project with an attendant increase in the available antiproton luminosity. Our typical running luminosity was then $5 \times 10^{30} \text{ cm}^{-2}\text{s}^{-1}$ in both $\bar{p}p$ and pp modes. A new vacuum chamber was installed between the target and the magnet; this was carefully designed according to the operating beam conditions we found in the Collider in order to minimize background and secondary interactions. We also added extra MWPC planes, and in an attempt to increase our spatial resolution, and reduce ambiguities in pattern-recognition in the calorimeter, we introduced three planes (u,v,z) of 1/2 cm width tubes near the shower maximum within the calorimeter (after 6 r.l.). Our photon/electron trigger was initially a hodoscope of 7 horizontal scintillator strips embedded 8 r.l. deep in the calorimeter. For 1985–1989 this was superceded by a fast processor trigger designed to search for localized showers by summing the energy deposited in a grid of overlapping horizontal and vertical strips of 12 neighboring calorimeter tubes. In 1990 this in turn was superceded by a trigger which took advantage of the development of high-quality optical fibers. This trigger used a mosaic of scintillator tiles (of typical dimensions

$10 \times 10 \text{ cm}^2$), also placed near the shower maximum, arranged in semi-circles relative to the beam position. Each tile had three or four wave-length shifting fibers embedded in surface grooves and fanned through clear fibers into phototubes mounted at the edges of the array. Signals from groups of neighboring tiles were summed and thresholds were applied, via computer-controlled discriminators, according to the geometrical position of each group. This allowed an approximately constant p_T trigger, which was crackless and had no dead-time, was more efficient at high p_T , less prone to confusion due to overlapped energy depositions and less sensitive to multiple interactions within the same bunch crossing than our previous triggers. Over time, the quality of the data written on tape has slowly improved.

1.4 Data analysis

We have published 5 papers so far. The data set on which each paper is based is listed below:

- Ref. [1]: 40 nb^{-1} hodoscope trigger data from each of the 1984 $\bar{p}p$ and 1986 pp data.
- Ref. [2]: 0.5 pb^{-1} 1985 $\bar{p}p$ data.
- Ref. [3]: 1984-1986 $\bar{p}p$ and pp elastic scattering data.
- Ref. [4]: data and test-beam data.
- Ref. [5]: 0.5 pb^{-1} 1985 $\bar{p}p$ and 1.5 pb^{-1} 1986 pp data.

Furthermore, there have been 4 PhD theses based on UA6, with another 6 graduate students planning to write theses on the the experiment in the coming years. Two of these students form a subsidiary effort at Lausanne and study the transputer-based trigger used in our final run. The latest thesis completes the study of direct photons from our 1985 and 1986 data sets; preliminary results were presented at conferences during 1990, and include the first ever measurements of the difference between the $\bar{p}p$ and pp direct- γ cross-sections (see Fig. 1). There is good agreement with theoretical predictions, and we can derive an expression for the gluon structure function in the nucleon, although these data are as yet only precise enough to determine Λ_{QCD} to within about 100 MeV.

The problem plaguing all direct-photon experiments is that of disentangling real direct photons from daughters of π^0 and η decays in which only one of the two γ s is detected, either due to one escaping from the detector, or the two merging within the resolution of the detector. This contamination of the candidate photons has to be modelled with a Monte Carlo simulation, which must be sufficiently sophisticated that its predictions for the "fake γ " contribution be credible. Essentially one must

have an efficient and well-understood reconstruction program, a realistic simulation of electromagnetic showers in the detector, and a good understanding of the agreement between the Monte Carlo and the real-world data. Our analysis has been slower than we would like due to two main causes: First, in 1987 the central CERN computing facility (on which our offline analysis is based) was switched from a CDC to an IBM system, necessitating a massive conversion effort, but which took about six months to complete. Second, the additional uv planes within the calorimeters did not turn out to be as easy to exploit as we expected. We have spent considerable time and effort in developing reconstruction methods making use of the information from these planes, while in parallel developing our existing analysis, and ensuring that both paths are consistent. Unfortunately, so far we seem to gain little improvement over the unmodified calorimeter. The problem seems to be that the extra planes do not constitute a calorimeter - they are only three planes of tubes - and although in electron test-beams they appear efficient at incident energies above about 8 GeV, in the considerably dirtier environment of the real experiment they seem to be only efficient above 20-30 GeV. This is where the old calorimeter tends to work satisfactorily anyway. This disappointing behaviour has only been understood slowly, and we are still loathe to just write-off the effort that has been expended on it. For these reasons we have refrained from starting the bulk data-processing of the 1988-1990 data. We now have all the information on reconstruction efficiencies and biases necessary to make a decision on which analysis path to follow. This decision is to be taken early in May; otherwise we are ready to start the full processing.

Meanwhile analysis has continued on the 1985 and 1986 data, leading to a thesis and a paper on J/Ψ production, and to the preliminary direct-photon cross-sections referred to earlier. Note that the MWPC information makes J/Ψ reconstruction from electron pairs easier, unlike the case of the direct-photon problem. With progressive development of our analysis and Monte Carlo (particularly with the input of electron test-beam data, photon data from reconstructed π^0 's, and Geant/EGS electron and photon simulation) we have obtained better and better understanding of the fake γ contribution to our gamma candidate sample. This has prompted us to reanalyze even the 1985 $\bar{p}p$ data, for which direct-photon results had already been published. This work is at last nearing completion (a thesis has just been completed), and we have enumerated a list of topics which must be studied and understood before final publication. This should take a number of weeks rather than months. Fortunately, this work is directly applicable to our later data sets and we foresee, perhaps optimistically, that analysis of these data will be somewhat more straightforward and much more rapid. We are also fortunate that one member of our group is collaborating with several theorists in extracting structure-function information from direct-photon data, which should speed the extraction of derivative physics results from our own cross-section measurements.

1.5 Rockefeller analysis contribution

The UA6 collaboration is a relatively small group: there have been at most 32 authors on our publications, and never more than 15 people working on data analysis. At present there are 9 people committing more than 50% of their time to this analysis:

<i>Institute</i>	<i>Personnel</i>
Rockefeller	1 assist. prof.
Michigan	1 grad. student
Yale	1 grad. student
CERN	1 senior physicist, 1 post doc
Lausanne	3 grad. students, 1 senior post doc

We have about 2500 6250-bpi tapes of raw data to be processed. Our analysis is centered on the CERN IBM 3090 system, with a subsidiary effort at a new VAX 9000 system recently installed at the Univ. of Lausanne. Our software has also been made fully-VAX compatible and we plan to share the major processing between the two systems. It is conceivable that about 50–100 tapes may be processed per week. As this processing advances, physics analysis can proceed in parallel so that physics results should be available soon after this processing is complete.

The role of the Rockefeller assistant professor (P.T. Cox) is central to this analysis. He develops and maintains analysis and utility programs, maintains data-base files of tapes, of calibration and of alignment information, has developed and maintains the controlling software for the large-scale data processing and is heavily involved in the direct-photon analysis. He has developed the Monte Carlo extensively, and has studied and analysed electron test-beam data leading to banks of electromagnetic showers which are used within the shower-simulation framework. He has also made preliminary studies of associated particle production in direct-photon events, with the object of studying the recoiling jets. We believe that the analysis effort is too small to be fragmented further, that this effort should be concentrated at CERN during the next stage of the analysis, and that it is essential that our assistant professor remain committed to this effort at CERN until mid-1992. By then the bulk processing should be complete, or nearing completion, and highly-compressed data-summary tapes should become available on which local analysis efforts, such as at Michigan, Rockefeller or Yale, could fruitfully be directed. Mid-1992 is also the time at which we can expect our first preliminary direct-photon cross-sections from the analysis of our full accumulated luminosity.

Graduate students have been assigned to the following topics from the full data sets of $\bar{p}p$ and pp : direct-photon cross-sections, J/Ψ production, and production of resonances with multi-photon decay modes. There also remain the topics of $\gamma\text{-}\gamma$ production and associated particles in direct-photon and J/Ψ production. Of course, the

direct-photon physics will aim at measuring the gluon structure function, as well as Λ_{QCD} , extracted from photon data, which should extend to p_T of around 7 GeV/c (x_T 0.3 – 0.6) with relatively small statistical and systematic errors.

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Figure 1: Preliminary direct- γ cross-sections and difference.

2 FERMILAB: The CDF Experiment.

2.1 Overview.

During the past year we have taken an active part in the upgrade program for the CDF detector, while continuing to analyze data from the 1988-89 collider run.

Our main analysis effort has been directed towards obtaining a value for the $\bar{p}p$ total cross section from the "small angle" data of CDF. These data were collected in special high- β runs with the apparatus described in detail in our CDF Note - 1291, which is attached to this report as an Appendix. We have made substantial progress in the understanding of the systematics of the small angle data, and our work has culminated in a CDF Note entitled "A Measurement of the $\bar{p}p$ Total Cross Section at $\sqrt{s} = 1800$ GeV". Our result was presented at the International Conference on "Elastic and Diffractive Scattering" in Elba, Italy (May 1991). This is the first result from the small angle data of CDF to be presented at a conference.

In addition to the measurement of the total cross section, we have searched for the η_6 particle in the CDF "L0-Query" data, the trigger-bias-free data of the 1988-89 run. The η_6 particle is a sextet quark state postulated in order to explain the Mini-Centauro and Geminion type events observed in cosmic ray experiments and, indirectly, to account for the high ρ -value in $\bar{p}p$ elastic scattering as has been reported by the UA4 experiment at CERN. A CDF Note entitled "Search for the η_6 Particle" has been written and these results were also presented at the Elba conference.

In the CDF upgrade program we have concentrated on the plug-calorimeter project. This project is to construct a scintillator tile calorimeter, read out with wave-length shifting fibers, to replace the present gas calorimeter. A prototype has been designed, is currently under construction, and will be tested in a test-beam this summer. Our specific responsibilities in this project are (a) the splicing of wave-length shifting fibers to clear fibers and (b) the preparation of the photomultipliers.

As a complement to the plug calorimeter, we have designed a tile/fiber "Microplug" calorimeter intended to cover the presently uninstrumented region of polar angles $0.5 < \theta < 2$ degrees. This calorimeter would be placed between the beam pipe and the forward calorimeter of CDF, at a distance of 6 m from the interaction point. The Microplug would be useful in searching, for example, for η_6 -type particles, while at the same time it would provide useful information on radiation damage to the scintillator during the course of the next run. A proposal to incorporate such a calorimeter in the detector is being submitted to CDF.

In addition to the above analysis and hardware projects, we have participated in the general process of getting CDF papers to the publication stage; since our last year's progress report, three more papers have been published by the CDF Collaboration [1-3]. One further activity by members of our group has been to participate in the preparation of the CDF Upgrade Proposal.

Below we discuss in some detail the analysis and the hardware activities specific to our group.

2.2 Analysis

2.2.1 Small Angle Physics

Our main objective in this area has been to measure the $\bar{p}p$ total cross section at $\sqrt{s} = 1800$ GeV. This measurement can be accomplished in two ways, both of which make use of the optical theorem

$$\left(\frac{dN_{el}}{dt} \right)_{t=0} = L \frac{\sigma_T^2 (1 + \rho^2)}{16\pi} \quad \text{Optical Theorem} \quad (1)$$

where L is the machine luminosity and ρ the ratio of the real to imaginary part of the forward elastic scattering amplitude.

(a) Luminosity-Dependent Method (LDM).

In this method, the differential elastic scattering rate is measured over some range in the small t -region, extrapolated to $t = 0$, and the cross section is evaluated from the optical theorem:

$$\sigma_T = 16\pi \left[L \frac{(dN/dt)_{t=0}}{1 + \rho^2} \right]^{1/2} \quad (2)$$

The advantage of this method is that, since σ_T depends on $L^{1/2}$, only 1/2 of the uncertainty in L contributes to the error in σ_T . The same is true for the uncertainty due to the $(1 + \rho^2)$ term. This is rather important, because ρ is not measured in our experiment and its value is the subject of some controversy at $\sqrt{s} = 540$ GeV, where the UA4 experiment reported the anomalously high value of $\rho = 0.24 \pm 0.04$. At $\sqrt{s} = 1800$ GeV a "normal" value (consistent with analyticity) would be expected to be $\rho \sim 0.15$, for which $(1 + \rho^2)^{1/2} = 1.01$. For $\rho = 0.24$, $(1 + \rho^2)^{1/2} = 1.03$. The difference of 0.02 between these two numbers is a measure of the fractional uncertainty in σ_T due to lack of knowledge of ρ . In the luminosity independent method discussed below, the $1 + \rho^2$ term enters directly, and therefore the uncertainty due to ρ becomes more significant.

An accurate measurement of σ_T with both methods can, in principle, measure ρ by demanding consistency between the two values of σ_T . However, the accuracy required to obtain a useful measure of ρ using this method is beyond the reach of this experiment.

(b) Luminosity-Independent Method (LIM).

In this method, the differential elastic scattering rate is measured simultaneously with the total event rate, N_T . Since

$$N_T = L\sigma_T \quad (3)$$

by dividing (1) by (3) one obtains a formula for evaluating σ_T which is independent of the luminosity:

$$\sigma_T = \frac{16\pi}{1 + \rho^2} \frac{(dN/dt)_{t=0}}{N_T} \quad (4)$$

The total rate is the sum of the elastic and inelastic rates

$$N_T = N_{el} + N_{in} \quad (5)$$

The elastic rate is obtained by integrating the fit to the dN_{el}/dt data. The inelastic rate has contributions from "hard core" non-diffractive collisions, from single diffraction and from double diffraction dissociation. These contributions, which have very different event topologies, must be measured simultaneously. In last year's progress report we outlined the difficulties involved in making this measurement and the detailed steps that we undertook to overcome these difficulties. This work is now nearing completion and is expected to yield a result sometime this summer. Meanwhile, the Rockefeller group has succeeded in completing a full LDM analysis, which led to a determination of σ_T at $\sqrt{s} = 1800$ GeV. This result was "blessed" by the CDF collaboration for presentation at the Elba conference (May 1991). Details of this work have been described in a CDF Note [4]. Below we discuss the main points of our analysis and the results that we have obtained.

The $\bar{p}p$ total cross section at $\sqrt{s} = 1800$ GeV.

In order to determine σ_T by the LDM one must measure the luminosity and the value of $(dN_{el}/dt)_{t=0}$ (see Eq. 2).

Last year we reported our work on the machine luminosity, details of which can be found in CDF Note - 1202. That work provided the calibration for determining the absolute scale of the machine luminosity for low- β collider operation with an accuracy of $\pm 6.8\%$. However, judging from our elastic scattering rate, the luminosity at high- β (where our small angle data were taken) seemed to be about 35% too high.

Once the low- β luminosity was well understood, the inconsistencies at high- β were traced back to an accelerator computer program, which inadvertently used erroneous lattice parameters during our high- β run. With this problem solved, we then focused

again on the elastic scattering analysis which was reported to the collaboration in May 1990 (CDF Note - 1201). The analysis procedure was not altered. However, a number of additional checks have been made, which provided us with a better understanding of the systematic errors. In particular, we have examined the effect of the overall alignment angle of our forward spectrometers relative to the beam. This was done by assuming that the beams crossed the interaction region at a small angle relative to the nominal beam orientation in the horizontal plane. For every assumed "beam-tilt" angle we recalculated the acceptance, rebinned the data and extracted the optical point. We found that, as expected, the elastic cross section for each spectrometer arm varied as a function of beam-tilt angle, with the two arms yielding the same cross section for an angle of $-4 \mu\text{rad}$ (Fig. 1a). However, the value of the optical point for the combined data of the two arms is quite insensitive to the beam-tilt angle (Fig. 1b). After performing several other checks, we presented our work to the CDF collaboration and received formal permission to present the following preliminary results at the Elba conference:

$$\sigma_T = 72.0 \pm 3.6 \text{ mb} \quad (\pm 1.7 \text{ stat}, \pm 3.1 \text{ syst})$$

$$\sigma_{el} = 16.5 \pm 1.5 \text{ mb}$$

$$b = 16.5 \pm 0.8 \text{ (GeV/c)}^{-2} \quad (\pm 0.5 \text{ stat}, \pm 0.6 \text{ syst}).$$

These values are in agreement with the values reported by another Tevatron experiment, E-710, namely $\sigma_T = 72.1 \pm 3.3 \text{ mb}$, $\sigma_{el} = 16.6 \pm 1.6 \text{ mb}$ and $b = 16.3 \pm 0.5 \text{ (GeV/c)}^{-2}$.

Our next step is to attempt to improve our understanding of the systematic errors, while at the same time to continue our ongoing work to determine σ_T (and the diffractive cross section) by the luminosity independent method.

2.2.2 Search for the η_6 Particle

The η_6 is a sextet quark state whose existence has been postulated to explain the Mini-Centauro and Geminion type events reported by cosmic ray (CR) experiments and, indirectly, account for the abnormally high ρ -value of $\bar{p}p$ elastic scattering at $\sqrt{s} = 540 \text{ GeV}$ reported by the UA4 experiment.

The η_6 is predicted to be produced diffractively. Since the Centauro and Geminion type events are identified as the hadronic and 2γ decay modes of the η_6 , its mass is set by the CR observations to be $\sim 30 (\pm 10) \text{ GeV}$, and its production threshold $\sim 450 \text{ GeV}$. Such a new high energy threshold could account for the large value of ρ at $\sqrt{s} = 540 \text{ GeV}$ if the η_6 production cross section were large (a few mb).

We have searched for the η_6 in a sample of $\sim 6,000$ CDF events that were collected without any trigger bias. The search was performed by looking for high p_T γ 's ($p_T > 5$ GeV/c) from the 2γ decay mode of the η_6 :

$$\begin{array}{c}
 \bar{p} + p \rightarrow X + \bar{p}(p) \quad \leftarrow \text{diffraction dissociation} \\
 \downarrow \\
 \rightarrow \bar{p}(p) + \eta_6 \\
 \downarrow \\
 \rightarrow 2\gamma
 \end{array}$$

Some comments on the theory of the η_6 (including references) and details on the data analysis are given in CDF Note - 1437 [5]. Our preliminary result, which has been "blessed" by the CDF collaboration for presentation at the Elba conference, is a limit on the product σB (production cross-section times branching ratio for $\eta_6 \rightarrow 2\gamma$). This limit is a function of the mass of the η_6 , which affects the kinematics and hence the detector acceptance. Fig. 2 summarizes our findings. An η_6 of mass in the range 20-40 GeV with a production cross section of a few mb, as predicted by its proponents, is excluded by this search. However, it is still possible that such an object could exist at the lower end of the predicted mass range if its production cross section were smaller. In section 2.3.2 we discuss a proposal to add a small, very forward calorimeter to the CDF detector that could be used to explore the region of small cross sections for even smaller mass η_6 -type particles.

2.3 Hardware

Our group has been involved in hardware projects ever since we joined CDF.

Initially, we built more than 1,000 channels of preamplifiers for the silicon strip detectors used in the small angle spectrometers. Later, when it was decided to add drift chambers to the spectrometers, we built the chambers, the scintillation trigger counters, and the mechanical units that housed these detectors. A total of 18 chambers and 28 scintillation counters, all built at Rockefeller, were employed in our apparatus.

We also took the responsibility of providing for the 1988-89 collider run the beam pipe assembly for the CDF collision hall, which included a 24' beryllium section. This project was followed all the way through, from the design stage to installation. In addition, we participated in the specification and testing of a second beryllium pipe acquired in 1990 to accommodate the silicon micro-vertex (SVX) detector.

With the small angle experiment coming to completion, our hardware interests have shifted towards calorimetry. During the past year we have concentrated in the CDF plug calorimeter upgrade program, where our major contribution has been in fiber splicing. Simultaneously, we have designed and constructed a full-scale model for a "Microplug", a small calorimeter intended to cover the presently uninstrumented

region of $0.5 < \theta < 2$ degrees.

2.3.1 Plug Calorimeter Upgrade

In the CDF plug calorimeter upgrade program, the present gas calorimeter is to be replaced by a scintillator tile calorimeter, read out with wave-length shifting (WLS) fibers. These fibers are spliced to clear fibers to carry the scintillation light to the photomultipliers (PM's). Currently an R&D program is underway to determine the best way of constructing such a calorimeter. A full scale sector of a plug prototype has been designed and is being assembled at Fermilab, with the goal of testing it in a beam during the forthcoming fixed target run scheduled for this summer.

The principal components of the tile/fiber calorimeter are the mechanical framework, including the absorber, the scintillator tiles, the read-out fibers and the photomultiplier assemblies. The plug prototype has about 2,000 tiles. A green WLS fiber is embedded in each tile in the form of a U, with the two ends of the U spliced to clear fibers that carry the light to the PM's (Fig. 3). Our group has taken responsibility for the splicing of WLS fibers to clear fibers and for the PM assemblies.

(a) Fiber Splicing

In making a splice, the goal is to achieve long-term mechanical stability, efficient light transmission through the splice and uniformity among different splices. Since the number of splices to be made is large (about 4,000 for the prototype and 100,000 for the final calorimeter), a machine is being used capable of making consistently good joints at the required production pace. The machine has been developed and built at Rockefeller. Quality control is maintained by a precision optical measurement of the light transmission of every splice.

A schematic drawing of the splicing machine is shown in Fig. 4. The splice is made by applying heat to the fibers abutted in a quartz tube under vacuum. In order to splice the WLS fibers already embedded in the tiles to 5 m long clear fibers, a "clam" type machine had to be developed, in which the quartz tube actually consists of two halves, cut along the tube axis. The machine "opens" to accept the fibers to be spliced, then it closes down to a "single" quartz tube and the filament is heated until the fibers are fused together. After the splice is cooled down, the machine opens again to free the fused fibers and accept the next set for splicing. This sequence, which is controlled by a microprocessor, takes about 25 sec.

From the 4,000 splices needed for the prototype about 2,000 have already been made. The production rate of finished splices is about 25/hr. Only about 0.5% of the joints have to be rejected as unacceptable. The light transmission of accepted joints is about $90 \pm 2\%$ (Fig. 5a). The overall measured spread in light transmission for splices made for the hadron calorimeter of the plug prototype, including fluctuations due to the UV light source used in the measurement and to the 5 m length of clear

fiber employed, is about 6.5% (Fig. 5b). Only a limited number of interventions on the splicing machine were necessary to keep a steady production pace. Typically, the filament has to be replaced every 3-4 days.

Overall, the performance of our splicing machine has been excellent. We are currently continuing the splicing work for the prototype, while at the same time developing the machine further in preparation for the high volume of splicing required for the actual plug calorimeter.

(b) Photomultipliers

In addition to fiber splicing, we have taken responsibility for the PM's of the CDF plug calorimeter prototype. A total of 72 PM's will be employed in the prototype. Our group made available to CDF 80 PM's (RCA 8575), which were taken from the apparatus of one of our previous Fermilab experiments, E-612.

This project involves selecting the PM's from a group of about 100, finding the operating voltage, testing for long term stability, linearity, and uniformity of the photocathode, selecting a "light mixer", and designing the PM mounting assemblies. In addition, 40 new PM bases were constructed in our laboratory and were added to about 60 bases taken from E-612, bringing the total number of bases to 100.

Fig. 6 shows a PM assembly. The fibers from a calorimeter tower are strung through holes in a nylon "cookie" and glued in place. The cookie is then faced with a diamond fly-cutter. There are 23 holes in the cookie, with each hole accepting the fibers from the tiles of one of the 23 layers of the tower. The light transmitted to the phototube from each layer is equalized to that of other layers by means of a grey scale mask on the front face of the cookie in order to achieve "longitudinal uniformity" for the calorimeter (equal light output efficiency per layer along the direction of the shower). After the mask, the light goes through a "light mixer", the purpose of which is to illuminate the photocathode uniformly, independent of the location of the fibers on the surface of the nylon cookie. The importance of the light mixer is illustrated in Fig. 7, which shows the photocathode uniformity of one PM for light arriving directly on the face of the phototube and for light going through the light mixer.

2.3.2 Microplug Calorimeter Proposal

Recently we have worked on a proposal to build two small electromagnetic calorimeters, using the tile-fiber technique, to "plug" the holes of the present Forward Electromagnetic (FEM) calorimeters of CDF all the way down to the beam pipe for the 1991 collider run. The proposal, which is being presented to the collaboration as a CDF Note [6], has been written by CDF members from Tsukuba(Japan), Texas A&M, Fermilab, Purdue, UCLA and Rockefeller. These "microplug" calorimeters, which are inexpensive and easy to build, can address some very interesting physics questions. In addition, they can be used to provide an "on-line" test of the tile-fiber technique.

(a) Physics.

The microplug can be used to search for events with high ET electromagnetic clusters in the very forward region. Such clusters could probe "exotic" physics processes, as for example the 2γ decay mode of the η_6 discussed in section 2.2.2.

The η_6 is just an example of what might lie beyond the rapidity region covered by our present calorimeters. For a complete discussion of the physics possibilities at large rapidities the reader is referred to the proposal submitted recently to the SSCL by J. D. Bjorken on "A Full-Acceptance Detector for SSC Physics at Low and Intermediate Mass Scales".

(b) Test of the tile-fiber technique.

The microplug calorimeter can be used to test the tile-fiber technique during actual running conditions. Checking stability over long time periods, tracking down possible changes in calibration, and measuring radiation damage to the tile-fiber assemblies through the course of the run could prove to be very useful in preparing us to meet the problems that may lie ahead in running with the new plug calorimeter.

The proposed microplug is a lead-scintillator-fiber EM calorimeter. A schematic drawing is shown in Fig. 8. Its shape is octagonal to match that of the FEM hole. It comprises eight towers, each consisting of 12 layers of 1/4" thick trapezoidal scintillator tiles sandwiched between 3/8" lead absorber plates. The scintillator light is collected from the tiles and transmitted to the PMT's through wavelength shifting fibers.

In order to determine the position of the EM showers and hence the ET of the γ 's, we plan to incorporate a position detector at shower maximum. For this purpose, we have designed a simple detector that measures only the radial position of the EM shower. A schematic drawing of this detector, including a figure that explains the principles of its construction and operation, is shown in Fig. 9.

To check for radiation damage and monitor the calibration during the run, radioactive sources at the ends of driver wires will be used, capable of "illuminating" all tiles of selected towers of the microplug. The Purdue design, employed in other CDF plastic scintillator calorimeters, will be implemented. Each ϕ -sector (tower) will be monitored by a separate source.

In the present design, the microplug and position detectors are easy to build. We have constructed a full scale plexiglass model of both detectors to check our design and we are confident that the project, if approved by CDF, can be completed within a period of 3-4 months, in time for installation for the next CDF run. A partially instrumented detector could be available for the test beam by the end of the summer.

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(a) Elastic cross section versus beam-tilt angle for each spectrometer arm

(b) The optical point versus beam-tilt angle for the combined data of both spectrometer arms

FIGURE 1

CDF Work in Progress

FIGURE 2 $\sigma(\eta_6 \rightarrow \gamma\gamma) / \text{Upper Limit}$

FIGURE 3
Tile-fiber assembly

Splicing Machine - Schematic Drawing

FIGURE 4
Fiber-splicing machine

FIGURE 5

- (a) Percent light loss through spliced fiber joints
 (b) Normalized light transmission through fiber joints:
 fluctuations include those from the 5m long clear
 fibers used in the sample under study.

FIGURE 6

LIGHT COLLECTION EFFICIENCY **AS A FUNCTION OF RADIUS AND ANGLE** (DIRECTLY ON PHOTOCATHODE)

(WITH 1 1/4" x 1 1/4" x 3/4" COOKIE)

FIGURE 7

Relative efficiency of light collection by the photocathode of an RCA-8575 photomultiplier as a function of radius and (relative) angle (normalized to the center of the photocathode)

MICROPLUG

schematic drawing

FIGURE 8

Microplug Shower-Max Detector

SHOWER-MAX DETECTOR (construction principle)

FIGURE 9

The shower-maximum position detector is constructed from a single piece of $\frac{1}{4}"$ thick scintillator, which is "separated" into circular strips by $\frac{3}{16}"$ deep grooves (the heavy lines in the figure). The strips are sectioned into quadrants, which are "viewed" by WLS fibers embedded in shallow grooves (thin circular lines).

3 SSC

3.1 Preshower Detector Development

Two members of the Rockefeller Group have been studying the use of early shower development (preshower) information for particle identification and EM shower position resolution. The original motivation for the project was to investigate the possibility of detecting synchrotron radiation photons with a Pb/scintillating fiber preshower detector, and using this signal to identify electrons. This work was supported by the SSC Generic R&D program, and was done in collaboration with a group from Yale University, who took responsibility for testing the Fastbus readout electronics, the online data acquisition system and the Monte Carlo simulation program.

The preshower detector, a picture of which is shown in Fig. 1, was built in our workshop. The detector, with 8 fiber super-layers separated by lead sheets of $1/4$ radiation length (RL) thickness, is also shown schematically in Fig. 2a. Each super-layer had 6 layers of 200, 0.5mm diameter fibers: two vertical layers, two at -15° and two at $+15^\circ$ to the vertical. Scintillation light from the individual fibers was converted to an electronic signal using two image intensifier chains each coupled optically to four CCD's (Fig. 2b). The readout chain consisted of an image intensifier which demagnified the image from 80mm at the front window to 18mm at the exit window, followed by a second image intensifier which used proximity focussing and was equipped with a chevron (two stage) micro-channel plate. The optical gain of the chain was approximately 10^5 . The output of the second image intensifier was divided into four quadrants and the image from each quadrant was sent to a CCD using a fiber optic light guide.

The eight Fastbus boards were built in our electronics shop. The boards were copies of the Fastbus digitizer boards developed at Cambridge University for the UA2 experiment at CERN. They were of a mixed analog and digital design, whose purpose was to digitize the CCD analog signal and to map the digitized information from CCD pixel to fiber format.

The fiber ribbons were also constructed at Rockefeller. Each ribbon consisted of two layers of 500μ diameter fiber at a 550μ pitch. The two layers were offset from each other by one half of the pitch. The fiber winding technique and glueing sequence were developed over the course of about 3 months. This technology has been transferred to Bicron, who have now provided us with 1.0mm diameter fiber ribbons, manufactured in the same fashion, for the prototype that we are building for the forthcoming SDC tests at Fermilab.

Figure 2c shows the test beam configuration used to collect data during March and April 1990 at the Fermilab TPL beam line. The beam provided electrons with energies between 10 and 200 GeV. Figure 3a shows the transverse shower profile of a 200 GeV electron for the eight $1/4$ RL super-layers, from 0 to 1.75 RL in depth. High energy electron data (50 to 200 GeV) were also taken with a bending magnetic field of 2.0 and

2.5 Tesla over 1.8 meters in order to produce synchrotron radiation. Figure 3b shows the transverse shower profile versus depth for a 200 GeV electron traversing the 4.5 Tesla-meter field. The synchrotron radiation is evident to the left of the main shower (the electron was bent to the right).

The data have been analyzed and preliminary results have been presented at several conferences¹. One result, relevant for preshower applications at the collider experiments, uses the energy deposited in the last super-layer at 1.75 RL to separate electrons from charged π 's (see distributions in Fig. 4a). Figure 4b shows the electron efficiency, for 10 and 200 GeV electrons, and the pion rejection versus the cut on energy in the 1.75 RL super-layer. One can reject 93% of the charged pions, while keeping 93% and 97% of the 10 and 200 GeV electrons respectively. Another preshower result, using only the energy weighted centroid from the super-layer at 1.75 RL, is that the electron shower position resolution is approximately 0.9mm, and the average rms shower width is approximately 1.4mm. The shower position resolution and width are only slightly dependent on the electron energy, for our energy range of 10 to 200 GeV.

More recently, the synchrotron signal has been analyzed by summing all the energy to the left of the main shower. Figure 5a shows distributions of this measure of synchrotron energy for 100 and 200 GeV electrons from data taken with the 2.5 Tesla (4.5 Tesla-meter) field, and charged pions for comparison. Figure 5b shows the average values of the synchrotron energy distributions for electron energies between 50 and 200 GeV, and with 0.0, 2.0, and 2.5 Tesla fields (the charged pion signal is shown for calibration at the zero GeV point on this graph). Figure 5c shows the electron efficiency for 100, 150, and 200 GeV electrons with 2.0 and 2.5 Tesla fields, and the pion rejection versus the cut on energy to the left of the shower. In the case of the 2.5 Tesla field, electrons with energy above 150 GeV can be identified with greater than 94% efficiency, while rejecting 93% of the charged pions. A NIM article, including the details of the synchrotron radiation results and comparisons with Monte Carlo simulations, is currently being prepared.

The experience gained by this Generic R&D Preshower project has motivated us to propose a preshower or shower-maximum detector for the SDC detector. The Rockefeller group is actively involved in both the preshower/shower-maximum SSC subsystem² (Rockefeller, Yale, Northeastern, Saclay, South Carolina, and UCLA), and the development of such a system specific to the SDC. These detectors would sample the energy and transverse distribution of an EM shower at a depth somewhere between 2.5 RL (preshower) to 6.0 RL (shower-max). This information would improve single γ position resolution and track-shower matching, increase π/e rejection, distinguish single γ 's from π^0 's, and aid in identifying non-isolated electrons. This would contribute toward $H \rightarrow \gamma\gamma$, heavy flavor, and $W\gamma$ physics. Detailed physics arguments and simulations for preshower and shower-maximum detectors within the SDC are contained in a SDC note³.

We are building prototypes of both types of detectors (preshower and shower-max)

to be tested at FNAL this summer in conjunction with the prototype SDC EM/Had tile calorimeter⁴. The Rockefeller group is building the prototype preshower detector, which is shown schematically in Fig. 6. The fiber ribbons, made by Bicron, consist of two layers of 100, 1mm diameter scintillating fibers at a 1.3mm pitch, where the top layer is nested within the bottom layer and is offset by one half the pitch. There are two super-layers, each consisting of 3 ribbons (horizontal, and $\pm 15^\circ$). One end of each of the 1200 fibers will be read out with an image-intensifier/CCD system similar to that of the previous detector. The pictures in Fig. 7 show the fiber ribbons mounted at their appropriate stereo angles, and the fiber ends going into the image-intensifier plate. The other end of each fiber will be read out by multi-anode photomultipliers (Phillips), Avalanche Photo-Diodes (APD), or conventional photo-multipliers.

Our goal for the test beam this summer is to determine the performance of a realistic preshower and shower-maximum detector in conjunction with EM and Had calorimetry information. The performance will be evaluated with material simulating the SDC coil, and several possible optical readout alternatives. Based on the results, a decision will be made on whether to construct a preshower or shower-maximum detector for SDC, and on how to design the appropriate detector. Regardless of the decision, our Rockefeller group intends to play a major role in the development of the final detector for SDC.

3.1.1 References

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Figure 1. Picture of E798 Detector:

Shows 4800 fiber ends going to CCD grid and PMT's.

Figure 2a. Schematic Drawing of E798 Preshower Detector

Figure 2b. Electro-Optic Readout

Figure 2c. E798 Test Beam Configuration

28/05/91 15.12

Figure 3. Superlayer vs Fiber Position

a) Without Synchrotron, B = 0.0 Tesla

b) With Synchrotron, B = 2.5 Tesla

Figure 4a. Distribution of Energy at 1.75 RL: solid line = π^+ ; dotted line = 10 GeV e^- ; dashed line = 200 GeV e^- .

Figure 4b. Electron Efficiency and Pion Rejection Versus Cut on Energy at 1.75 RL.

Figure 5a. Distribution of Energy Left of Shower for $B = 2.5$ Tesla:
solid line = π^+ ; dotted line = π^- ; dashed line = e^- .
100 GeV e^- ; 200 GeV e^- .

Figure 5b. Synchrotron Energy versus Electron Momentum and Bending Field.

Figure 5c. Electron Efficiency and Pion Rejection versus Energy Left of Shower

All units in mm

ALL CABLES
GO TO
BULK-HEAD
FEED-THROUGHS
ON SIDE WALL

Figure 7. Pictures of SDC Prototype Preshower Detector:
top - shows fiber ribbons at stereo angles;
bottom - shows fiber ends going into II/CCD plate

3.2 Development of High Pressure Gas Calorimetry

3.2.1 Motivation

A few years ago we initiated an effort to examine the feasibility of constructing calorimeters with active medium noble gas at high pressure. The motivation for considering high pressure gas calorimetry arises after one reviews the other types of unity gain calorimetry (i.e. liquid argon, TMS, TMP) as well as the calorimetry with gas at one atmosphere. The liquid argon option requires cryogenics. D0 at Fermilab, the only 4-pi liquid argon calorimeter built thus far, has significant "dead" spaces. Also the electron drift velocity in liquid argon is rather poor (~ 250 ns/mm [1]) in terms of the number of SSC bunch crossings. As for the warm liquids, TMS is no longer seriously considered for any large experiment because of safety problems. TMP is still receiving major consideration by several groups. Its main disadvantage (as well as that of other warm liquids) is that it is very sensitive to impurities on the ppb level. This requires that the instrument be made of many sealed boxes, which makes it very expensive and results in a substantial fraction of "dead" area. It also requires very high operating voltages. The TMP electron drift velocity is about the same as for liquid argon at electric fields of about 2 KV/mm [1]. Also, under intense irradiation, i.e. $\sim 10^7$ rads (this level of radiation corresponds to about one year of running at a luminosity of $10^{33} \text{ cm}^{-2}\text{sec}^{-1}$, at a polar angle of 5 degrees and at a distance of about two meters from the interaction point [2]) radiolysis of part of TMS or TMP releases gaseous hydrocarbons that can build up to a moderate pressure (~ 6 atm) and may actually reduce the size of the collected signal [3].

Calorimeters with sampling medium gas at 1 atm have their own problems. Because of their extremely low energy sampling fraction ($\sim 0.01\%$), both the electromagnetic and the hadronic energy resolution are very poor ($\sim 30\%/\sqrt{E}$ and $\sim 140\%/\sqrt{E}$ respectively [4]) and, if hydrogen is present in the gas and/or in the walls of the chambers, protons scattered by slow moving neutrons in the hadronic showers and in the beam halo cause significant fluctuations in energy measurement. This phenomenon is known as "Texas Towers" and has been observed in the CDF gas calorimeters as well as in other gas calorimeters [5]. The gain of 1 atm gas calorimeters is very sensitive to many factors, among which we can mention the barometric pressure (1% change in barometric pressure results in a 7% change in gain for the CDF gas calorimeters).

Therefore it is very painful to control or even just to correct for such changes. Because of the fact

that the gain is too high (e.g 10^4 to 10^5 for the CDF gas calorimeters), wires in regions with high particle fluxes start drawing a lot of current (this problem is frequently referred to as "glow mode") which requires the chamber's voltage to be turned off for several minutes if not hours. Also, for the same reason, measures have to be taken to prevent the wires from being corroded.

One possibility that could avoid all of the above problems, while maintaining the main advantages of the calorimeters with sampling media liquid argon, TMS, TMP and 1 atm gas, is to use gas (like argon or xenon) at high pressure as a sampling medium. The pressure is so high that the density of the gas is only a few times less than the density at its liquid phase (for example 100 atm argon gas has a density of $\sim 1/8$ of liquid argon). However there are two basic questions to be answered before we get too serious about building a real calorimeter with a gas at high pressure as its sampling medium: (a) What is the highest pressure above which the signal becomes too sensitive to impurities (like in the case of the room temperature liquids), do we get enough signal at this pressure, and are the signals fast enough for the SSC? (b) Can one overcome the mechanical problems associated with high pressure gases and build a full scale calorimeter? In the following two sections we describe the work done thus far by our group to answer the above questions, we outline our present R&D effort and we sketch our future plans.

3.2.2 Results from a High Pressure Test Vessel

As of about two years ago not much was known about the behavior of gases at high pressures, especially with regard to the signal size vs pressure. We therefore decided to design and build a high pressure vessel and perform our own tests. A schematic diagram of the high pressure vessel is shown in Fig. 1. The radioactive material is implanted on the surface of a metallic plate ~ 2 cm in diameter. This plate is mounted on and is electrically connected to the cathode. A positive high voltage is applied to an equal size metallic plate across the cathode. The gap between the two plates can be varied from 2 mm to 10 mm. The measurements were done with 2.5 mm gap. Tests were performed with argon (Ar) and Ar + CH₄ gases in the pressure range of 7 to 160 atm and with an ²⁴¹Am source (alphas of 5.5 MeV).

The results have been reported in Ref. [6]. We summarize here the main features : (a) At 100 atm argon, the signal saturates at the comfortable field of 0.5 KV/mm. (b) The charge collection efficiency at 100 atm is 80% (it is expected to be larger with minimum ionizing particles for which the ion density and therefore the rate of recombination are much smaller). (c) The inverse of the electron drift velocity at 100 atm argon with 1% CH₄ and at 1 KV/mm electric

field is 60 ns/mm. (d) 100 parts per million (ppm) oxygen contamination in a 100 atm argon plus 1% CH₄ mixture causes a signal loss of only 10% while for up to 50 ppm oxygen concentration there is not appreciable loss in signal. Our calculations also showed that with 100 atm Ar + 1% CH₄ the produced electrical signal is large enough so that particles with energy down to a few hundred MeV can be detected [6].

3.2.3 Present R&D and future plans

Encouraged by the results we obtained with the high pressure vessel we decided to take the next step which is to design, build and test a high pressure calorimeter. Last November we were joined by two Soviet groups and one Illinois company. Our Soviet collaborators have had a lot of experience with high pressure calorimetry [7]. We submitted a proposal to the TEXAS NATIONAL RESEARCH LABORATORY COMMISSION (TNRLC) to build and test an 100 atm electromagnetic (EM) calorimeter [8]. This proposal was approved for full funding by the TNRLC in March 1991. In the meantime the SDC (Solenoidal Detector Collaboration), in its Letter of Intent submitted to SSC last November, considered high pressure gas calorimetry as one of the options for its forward calorimeters [9]. We have therefore adjusted the design of our prototype EM calorimeter to match the requirements of an SDC forward calorimeter. Our current design calls for 10 cells with each cell made of two parallel, 1 inch thick each, steel plates. There is a 5 mm gap between the steel plates for the high pressure gas and the readout ceramic board. We are now constructing this calorimeter and we plan to test it in a Fermilab test beam during the coming fixed target run. The energy resolution for Ar, Ar + 1 % CH₄, Xe and Xe + 1 % CH₄ gases will be studied. We are performing at present Monte Carlo studies of the energy resolution of high pressure gas calorimeters. The program GEANT is being used. Our preliminary results show that the stochastic term in the energy resolution of an EM/hadronic calorimeter with the above design (1 inch steel plates, 4 mm argon at 100 atm) is 40%/sqrtE / 100%/sqrtE respectively. This resolution is quite adequate for the forward region at the SSC detectors.

Our future plans are : (a) To design and construct one cell with 1 inch thick steel plates and 2.5 meter in diameter, i.e. the full transverse dimensions of the SDC forward calorimeter on which to perform mechanical and electrical tests. We have asked SDC for financial support in FY1992 to carry out this project. (b) If our tests with our prototype EM calorimeter are successful we will ask for further support from TNRLC to build and test a hadronic calorimeter.

3.2.4 References

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Fig. 1. Schematic diagram of high pressure vessel and readout electronics.

3.3 The Silicon Drift Detector Project

About three years ago, in collaboration with physicists from Brookhaven, Milan and Munich, we started a program to develop high resolution silicon drift detectors with two-dimensional read-out for use in the UA-6 experiment at CERN. A Silicon drift detector is a fully-depleted silicon wafer in which ionization electrons from charged particle tracks drift under static electric fields towards an array of anodes.

Such detectors are of interest in high energy physics experiments because of two features: their low output capacitance, hence low electronic noise allowing good dE/dx measurements, and their capability of unambiguously attributing space points to tracks.

This project has been very successful. Prototype detectors have been built and tested both with an infrared laser and in a charged particle beam. Resolutions as good as $15\ \mu$ were obtained. A novel method of calibration of the drift velocity using direct charge injection was employed with excellent results [1]. A paper containing a critical analysis of the detector design and of the results of the tests has been accepted for publication in NIM [2] and is attached to this report.

Although the project has been completed too late for UA-6, our interest in it has been renewed in connection with our "Low p_T Physics" (EOI-2) "expression of interest" for the SSC. The detector proposed for this experiment consists of a bundle of scintillating fibers placed inside the SSC vacuum pipe so that the fibers are parallel to the beam. Protons from small angle elastic scattering and from single-diffraction dissociation traverse the fibers along the fiber axis yielding relatively large amounts of light. Thus, fibers of small diameter can be used, resulting in good position resolution. The conventional way of reading out scintillating fiber arrays is by using image intensifier tubes (IIT's) coupled to CCD's. For faster readout, our proposal [3] is to basically use silicon drift detectors in place of the CCD's, which will increase the read-out rate by a factor of about 1,000. This proposal has been accepted by the SSC and we have now started a new R&D program to develop such IIT/SDD hybrids.

3.3.1 References

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4 APPENDIX

4.1 The drift chambers and scintillation counters of the small angle spectrometers of CDF

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APPENDIX

THE DRIFT CHAMBERS AND SCINTILLATION COUNTERS OF THE SMALL ANGLE SPECTROMETERS OF CDF

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Abstract

We describe the design, construction and performance of the drift chambers and scintillation counters of the Small Angle Spectrometers of CDF, which have been used in conjunction with silicon strip detectors to measure elastic, diffractive and total cross sections at the Tevatron.

The study of leading particle processes, such as $\bar{p}p$ elastic scattering and single diffraction dissociation, requires accurate measurements of the angle and momentum of the "recoil" proton and/or antiproton. These "leading particles" have $\bar{p}_T \sim 0.2-0.3$ GeV and momentum close to that of the momentum of the beam, so that they are emitted at polar angles $\bar{\theta} \sim 250 \mu\text{rad}$. Because of their small polar angle, these particles may be conveniently analyzed by spectrometers employing the magnets of the machine itself. Two such "small angle spectrometers", consisting of detectors in "Roman Pots" stationed in positions along the Tevatron ring on both sides of the interaction point (IP), have been constructed, installed and operated during the 1988-1989 run of the Collider Detector at Fermilab (CDF). A schematic layout is shown in Fig. 1. The Pots containing the detectors were mounted on bellows so that they could be moved by remote control to positions close to the coasting beams after injection and acceleration, making it possible to measure momenta very close to the momentum of the beam^[1].

Elastic scattering is dominated by a large forward exponential peak characterized by a "slope parameter" b_{el} , which at $\sqrt{s} = 1.8$ TeV is ~ 17 $(\text{GeV}/c)^{-2}$. In single diffraction dissociation,

$$p + p \rightarrow p + X$$

the proton or antiproton is excited coherently into a high mass state X. In terms of the Feynman x-variable, $x = 2 p_{||}^* / \sqrt{s}$, the excitation mass is given by

$$1-x \approx M^2 / s$$

At ISR ($\sqrt{s} \sim 10-60$ GeV) and SPS Collider energies ($\sqrt{s} = 540$ GeV), the differential cross section $d^2\sigma/dt dx$ was found to have the approximate form

$$\frac{d^2\sigma}{dt dM^2} \sim \frac{1}{M^2} e^{bt} \quad (4)$$

where $b \approx 0.75 b_{el}$. At the Tevatron, one might therefore expect $b \approx 12$ $(\text{GeV}/c)^2$. The average $|t|$ of the diffractive states is thus $|t|_{ave} = 1/b \approx 0.1 (\text{GeV}/c)^2$. Since

$$|t| = p^2 \theta^2$$

this value of t corresponds to an average production angle of $300 \mu\text{rad}$ for 900 GeV beams at the Tevatron. The average production angle for elastic scattering is $200 \mu\text{rad}$.

At $\sqrt{s} = 1.8 \text{ TeV}$, masses as high as 0.7 TeV fall within the diffractive region $1-x < 0.1$. Although the production angles of the diffractive masses themselves are small, the angles of their dissociation products are generally quite large. The "decay" kinematics of SD are summarized in Fig. 2, which shows the expected shape of the pseudorapidity distribution of a diffractive cluster of mass M . The average η is $\bar{\eta}_M = \ln(\sqrt{s}/M)$. The average laboratory angle, obtained by using the relation $\eta = -\ln \tan(\theta/2)$, is given by

$$\bar{\theta}_M \approx 2 M/\sqrt{s} = 2 \sqrt{1-x}$$

Thus, masses in the range 2-700 GeV, tagged by the spectrometers, dissociate into particle clusters of average angles approximately 2-700 mrad. In CDF, the interaction region is surrounded by tracking detectors as shown in Fig. 3. These detectors are used to track charged particles associated with each non-elastic event.

The measurement of the inelastic rate is very important for the determination of the total cross section, more precisely of the quantity $\sigma_T(1+\rho^2)$, where ρ is the ratio of the real to the imaginary part of the forward nuclear scattering amplitude. By measuring simultaneously the differential elastic and total inelastic rates, $\sigma_T(1+\rho^2)$ is obtained by the "luminosity independent method",

$$\sigma_T(1+\rho^2) = 16\pi \frac{(dN_{el}/dt)_{t=0}}{N_{el} + N_{in}} \quad (7)$$

The differential elastic rate is measured over a certain region of (small) t , extrapolated to $t=0$ to obtain $(dN_{el}/dt)_{t=0}$ and then integrated to yield N_{el} . The inelastic rate is measured simultaneously with the elastic using the tracking chambers shown in Fig. 3.

III. THE SMALL ANGLE SPECTROMETERS.

The small angle spectrometers consist of detectors in "Roman Pots" located at appropriate stations along the Tevatron ring on both sides of the CDF interaction region (Fig. 1). The position of the Pots transverse to the beam is controlled remotely, so that they may be kept away from the beam during injection and moved close to it after stable coasting conditions are attained. This is shown schematically in Fig. 4. Particles created at the IP within a certain angular and momentum range are detected and their momentum is magnetically analyzed using the magnets of the Tevatron itself. The fractional difference of the particle's momentum from the momentum of the beam is related to the diffractive mass (see Eq. 3):

$$\frac{\Delta p}{p} = 1-x = \frac{M^2}{s} \quad (6)$$

The mass resolution, calculated from the momentum resolution, is given by

$$\frac{dM}{M} = \frac{d(\Delta p/p)}{M^2/s} = \frac{1}{2} \frac{dp}{p_{beam}} \frac{1}{1-x}$$

As shown in Fig. 1, the antiproton spectrometer comprises stations S1, S2 and S3, while the proton spectrometer consists of stations S6 and S7. Stations S4 and S5 are used to record charged tracks from inelastic collisions in the angular range 2-6 mrad (see Fig. 3). The two spectrometers are not identical. While the magnetic analysis on the antiproton side is done primarily with dipole magnets, only quadrupoles are used on the proton side. This choice was dictated by space limitations along the Tevatron ring. As a result, the momentum on the proton side can only be measured for particles that are emitted with some angle with respect to the beam, so that they enter the quadrupole field of the indicated magnets. These magnets comprise mainly the "low beta quads", and therefore leading proton momenta

can only be measured in low beta operation of the machine. In contrast, leading antiproton momenta can also be measured in high beta. Small angle antiprotons that do not register in station S3 can be analyzed by stations S1-S2 only. In this case, the origin of the leading particle is assumed to be at the interaction point, which is measured for each inelastic event by the tracking chambers. A zero constraint fit to the three points gives both the momentum and the angle, hence the t -value, of the antiproton. The same procedure is used for the analysis of leading proton momenta with stations S6-S7.

The acceptance of the spectrometers was calculated from the beam transport matrix of the Tevatron and a Monte Carlo simulation.

IV. DETECTORS

Each pot in stations S1,2,3,6,7 is instrumented with a drift chamber, a silicon strip detector and two scintillation counters for triggering (Fig. 5). The pots in stations S4 and S5 contain only a drift chamber and one scintillation counter (Fig. 6).

1. Drift Chambers

The chambers, each with four sense wires and a delay line, measure the x and y coordinates of traversing particles. Since the tracks of interest are nearly perpendicular to the beam, induced pulses from all sense wires have identical times and yield the same location along the sense wire direction. We therefore used a common delay line to "view" all four sense wires of a chamber. Figure 7 is a drawing of one of the spectrometer chambers. The chambers in stations S4 and S5 are of the same design, except that their active volume is U-shaped to allow maximum coverage around the beam (see Fig. 3).

Three novel features were incorporated into the design of the chambers:

- (a) The field shaping wires do not touch the inside surfaces of the G10 frame of the chamber except at the four corners; this feature, which is

achieved by carving the G10 frames as shown in Fig. 8a, safeguards against distortions due to surface charge on the G10.

(b) The sense wires are pre-mounted on an aluminum plate as shown in Fig. 8b; the prepared plate is inserted, like a cassette, into slots milled in the frame of the chamber (see Fig. 7). In addition to facilitating wire mounting and replacement, this design provides isolation of the wires from one another and guards against positive ion build-up.

(c) The delay line, which picks up an induced pulse coherently from all four sense wires, is also inserted into slots milled in the G10 frame of the chamber, as shown in Fig. 7. The design of the delay line itself is shown in Fig. 8c. The 0.004 inch magnet wire is wound around a "sandwich" of two G10 plates with copper-clad "inside" surfaces, which provide the ground return. The plates are 1/32 inch thick by 1 ⁵/₈ inch wide. The length of the line is 1 ⁷/₁₆ inch for the spectrometer chambers and 2 ¹¹/₁₆ inch for the chambers of stations S4,5. By supplying a ground return on both G10 plates, one guarantees uniform separation of the wire from the ground on both sides of the delay line. This design ensures uniform speed of propagation of the induced pulse along the line.

The delay time across the line was 4.4 nsec/mm, the rise time ~40 nsec and the characteristic impedance 1.2 K Ω . Preamplifiers for sense wire and delay line signals were mounted directly on the chamber flanges. These used the Fujitsu MB 43458 I.C.'s (Ref. VTPC article) and other surface-mount components for input projection and test pulse circuitry. A common emitter input circuit was used to provide proper termination and inversion for the delay line signals.

The electrical wiring of the chambers is shown in Fig. 9. The negative high voltage plate, which provides the drift field, is insulated from the pot by a sheet of mylar. The entire pot is filled with 50-50% argon-ethane gas at 1 atm. The silicon strip detector and scintillation counters, which are described below, are inadvertently immersed in the chamber gas.

2. Silicon Detectors

The silicon detectors are surface-barrier silicon diodes with electrode strips on both sides allowing two dimensional x-y read-out. The ohmic side is subdivided into 64 strips 50 μm wide separated by 500 μm . The junction side is segmented into 30 pads, 900 μm wide and 100 μm apart. The total active area is approximately 35 x 30 mm^2 . The complete strip structure on the ohmic side is surrounded by a 250 μm wide guard ring.

The diode is operated under reverse bias, so that the full thickness of the detector is depleted. The charge released by minimum ionizing particles traversing the 900 μm thick silicon wafer are collected by the electrodes; electrons are collected by the strips while pads collect holes. Strip and pad signals are fed into preamplifiers incorporating the HQV820 hybrid. The read-out system is based on a variation of the CDF "Rabbit" system. A detailed description of the silicon detectors has been reported elsewhere [2,3,4,5].

3. Scintillation Counters

The scintillation counters, which are used for triggering (see Figs. 5 & 6), are made of 1/8 inch thick BC-404 Bicron plastic scintillator. The light is guided by twisted-strip lightpipes into 1/2 inch diameter plexiglass rods viewed by phototubes. The lightpipe design and dimensions are shown in Fig. 10.

The entire detector assembly (chamber, silicon detector, scintillation counters) is mounted on a flange, which is used to seal the pot. The flange carries all connections to gas, high voltage supplies and read-out electronics (Fig. 11). The phototubes are on the outside face of the flange. Since the pots have to be gas-tight, an o-ring is pressed against the plexiglass rod lightpipe as it passes through a hole in the flange (piston seal).

V. DETECTOR PERFORMANCE.

The detector system, as a whole, performed extremely well. No problems appeared over the one year operation of the spectrometers during the run. Data were collected for the measurement of elastic, diffractive and total cross sections. The performance characteristics of the detectors were obtained from analysis of these data.

Elastic events were recorded by triggering on a coincidence between a $\bar{p}$ -arm ($S1*S2*S3$) on one side and a p-arm ($S6*S7$) on the opposite side of the Tevatron ring. With this trigger, the acceptance at large angles was limited by $S1*S2$. In order to extend the coverage to larger angles some data were taken with only $S3$ required on the $\bar{p}$ -arm.

The elastic signal was extracted by requiring that the tracks in the two spectrometers be collinear. Using elastic events, we measured the resolution and efficiency of the chambers. The single wire resolution was found to be $\pm 230 \mu\text{m}$ and the delay line resolution $\pm 800 \mu\text{m}$. By defining tracks with two out of the three stations on the $\bar{p}$ side and looking at the third station, the overall position resolution of a chamber was found to be $\pm 115 \mu\text{m}$, as expected from the single wire resolution for a 4-wire chamber. The single wire efficiency was found to be larger than 99% all the way out to about 300-400 microns from the cathode plane.

The silicon strips were very useful in providing a continuous calibration of the drift velocity for the chambers on a run-by-run basis, making it possible to keep the overall uncertainty in drift velocity to a level below 1%. The drift velocity was approximately $5.2 \text{ cm}/\mu\text{sec}$. The silicon pads were used to calibrate the chamber delay lines and correct them for a small ($\sim 4\%$) non-linearity.

The momentum resolution of the $\bar{p}$ -spectrometer, measured from elastic events by stations $S1,2\&3$, was found to be $\pm 0.3\%$, as expected.

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FIGURE CAPTIONS

- Fig. 1: Schematic layout of The CDF small angle spectrometers.
- Fig. 2: Schematic drawing of the charged particle pseudorapidity distribution of a diffractive cluster of mass M created in a $\bar{p}p \rightarrow \bar{p}X$ collision at $\sqrt{s}$.
- Fig. 3: The CDF tracking system.
- Fig. 4: Schematic layout of a station of "Roman Pots" on the beam line.
- Fig. 5: Arrangement of drift chamber, silicon detector and scintillation counters inside a "Roman Pot" in stations S1, 2, 3, 6, 7.
- Fig. 6: Drift chamber and scintillation counter arrangement inside a "Pot" in stations S4 and S5.
- Fig. 7: An exploded view of a spectrometer chamber
- Fig. 8: (a) Principle of field shaping winding.
(b) Sense wire plate "cassette".
(c) Delay line winding.
- Fig. 9: Electrical wiring of chambers.
- Fig. 10: Lightpipe design for scintillation counters in spectrometer pots (dimensions shown are in inches).
- Fig. 11: Photograph of a detector assembly mounted on a flange.

4.2 Performance of the UA6 large-area silicon drift chamber prototype