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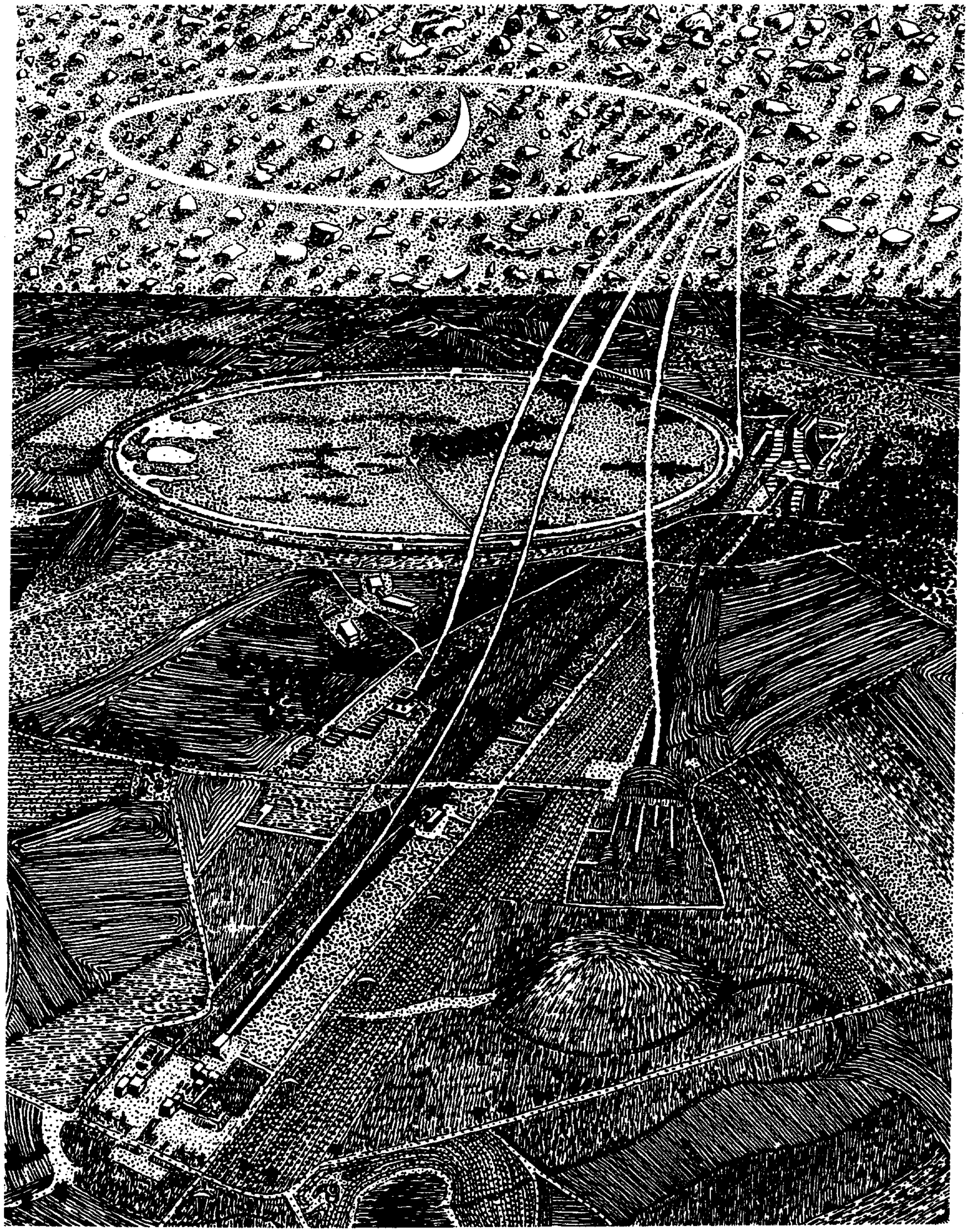
Symposium in Celebration of the

Fixed Target Program with the Tevatron



Fermi National Accelerator Laboratory

June 2, 2000

In Celebration of the Fixed Target Program with the Tevatron

June 2, 2000

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In Celebration of the Fixed Target Program with the Tevatron

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"The main application of the work here is spiritual, if you will. It's because, in a philosophical sense, in the tradition of Democritus, we feel we have to understand, in simplest terms, what matter is, in order to understand who we are."

Robert R. Wilson, 1974

ACKNOWLEDGMENTS

This book would not have been possible without the help of a large number of people. The many spokespeople from the experiments in this book, and their designees, have provided us with most of the material presented here. We also want to express our sincere appreciation to Sue Schultz for her lead in the typing, compiling, and formatting this book, as well as for putting up with all the variations of input and the diverse requests from the editors. We appreciate the encouragement of Judy Jackson who pushed for the "plain English" texts which have been prepared for each section and experiment, and the help of Jackie Coleman in the Directorate.

Appropriately, a drawing by Angela Gonzales appears on the cover of this book, since her artwork graced so much of the Tevatron fixed target era. We also thank Jenny Mullins and the Visual Media Department for providing the photos in the book.

Finally, we thank those who contributed material to this book. They include: R. Brock, D. Christian, M. Corcoran, B. Cox, M. Crisler, J. Cumalat, C. Dukes, G. Ginther, G. Gollin, N. Grossman, J. Hanlon, Y-B Hsiung, K. Johns, K-B Luk, B. Lundberg, K. McDonald, P. Nienaber, M. Purohit, S. Reucroft, H. Schellman, W. Selove, M. Shaevitz, P. Slattery, W. Smart, N. Stanton, B. Winstein, Y. Wah, J. Wiss, A. Yokosawa, and A. Zieminski.

FIXED TARGET PROGRAM

SYMPOSIUM PROGRAM
SECTION 1

Symposium in Celebration of the
Fixed Target Program with the Tevatron
Friday, June 2, 2000

9:00 Session I - Convener: Jeffrey Appel

Getting to the Tevatron
Leon Lederman, Illinois Mathematics and Science Academy
and Illinois Institute of Technology

Theoretical Questions during the Tevatron Era
Jonathan Rosner, University of Chicago

10:10 Break

10:35 Session II - Convener: Chuck Brown

Evolution of Tevatron Accelerator and Experimental Technologies
John Peoples, Fermilab

Physics, Dectectors, and the Rest in the Tevatron Hyperon and Kaon Programs
Bruce Winstein, University of Chicago

11:45 Lunch

1:15 Session III - Convener: Peter Cooper

Physics of the Heavy Quark Program
Jussara Miranda, Centro Brasileiro de Pesquisas Físicas

Physics of the Muon and Neutrino Programs
Heidi Schellman, Northwestern University

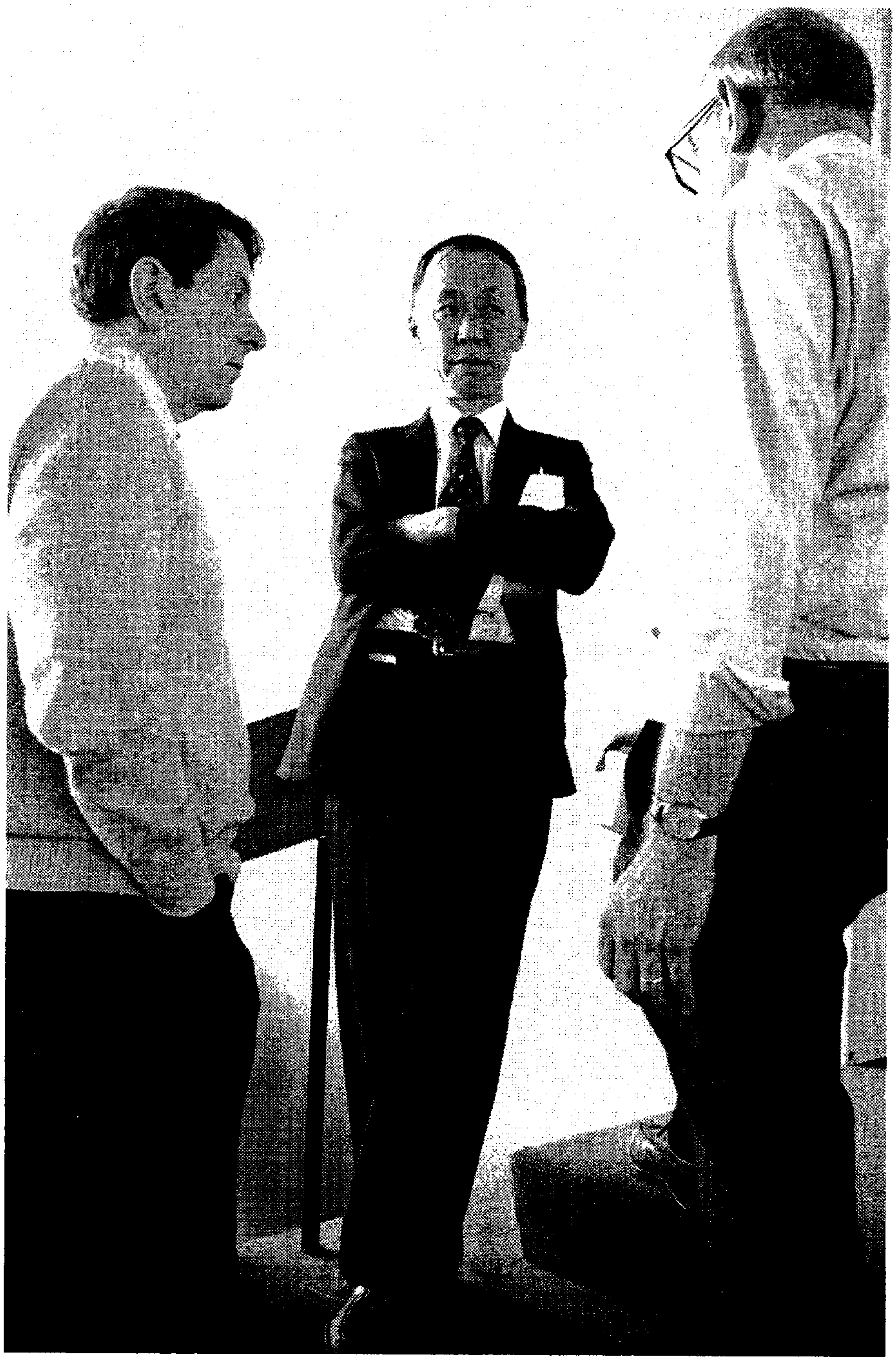
2:25 Break

2:50 Session IV - Convener: Herman White

Studies of High – Pt and High – Mass Phenomena
Paul Slattery, University of Rochester

Summary of Where We Are and What Lies Ahead for Fixed Target at Fermilab
Michael Witherell, Fermilab

4:00 Celebration in the Wilson Hall Atrium



INTRODUCTION TO THE TEVATRON FIXED TARGET PROGRAM SECTION 2

2. INTRODUCTION

The Tevatron is the world's first large superconducting accelerator. With its construction, we gained the dual opportunities to advance the state of the art in accelerator technology with the machine itself and in particle physics with the experiments that became possible in a higher energy regime. In 1989 President Bush presented the National Medal of Technology to four Fermilab physicists; Helen Edwards, Dick Lundy, Rich Orr, and Alvin Tollestrup for their work in building the Tevatron. This award at the highest level possible for a government project is recognition of the many contributions from the Fermilab staff to the success of the Tevatron project; from Bob Wilson at the beginning through all the scientists, engineers, and staff of what we now call the Beams and Technical divisions. They turned Bob's vision into a real accelerator.

On the first of October 1983, the first run of the Tevatron, the still-largest superconducting accelerator in the world, was just beginning. The commissioning run, at 400 GeV/c with 5 fixed target experiments in the Proton and Meson Laboratories, was a stepping stone to higher energy for fixed target experiments and, a few years later, to the collider program.

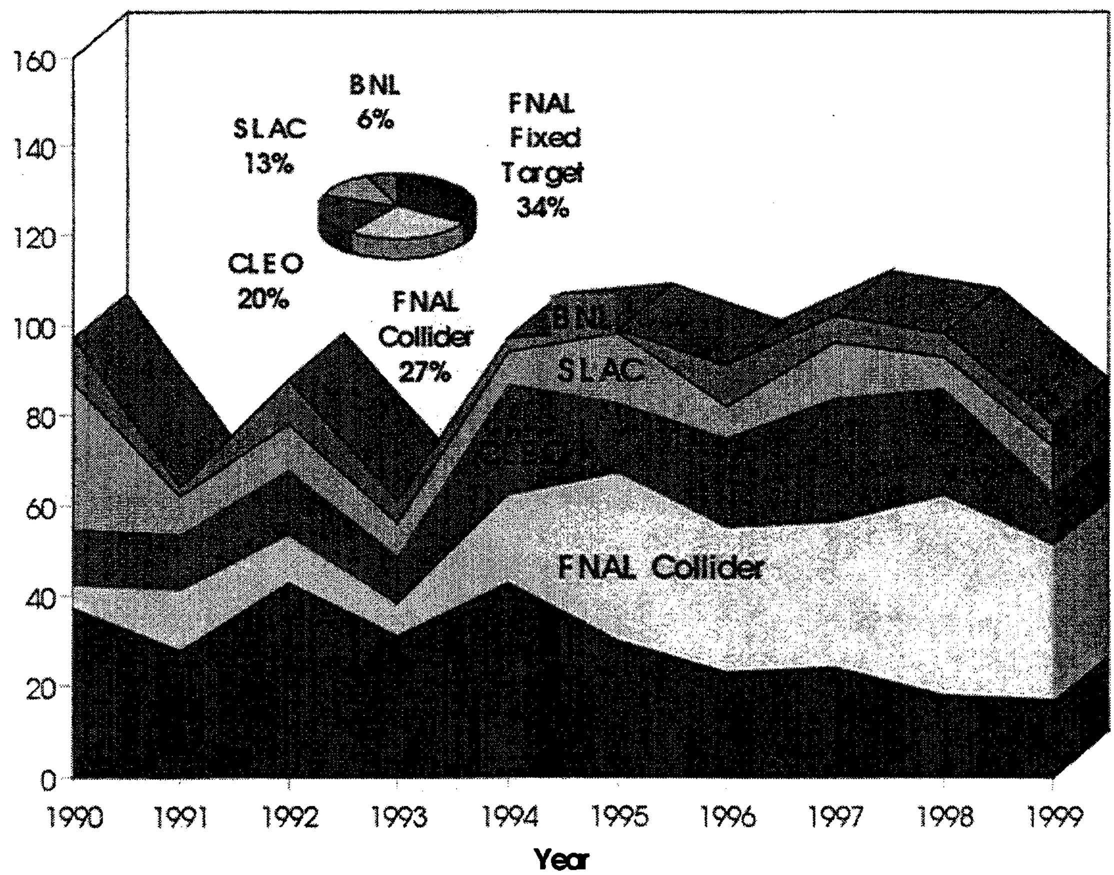
At 00:40 the message on channel 13 read "NO BEAM TO PROTON FOR AT LEAST 3 HRS". In fact there were only 26 hours of beam delivered in that first month. This was quite frustrating to those sitting midnight shifts at the time, both at the experiments and in the accelerator control room.

However, it was also a tour-de-force in bringing together the technological frontier of industrial scale superconductivity and the energy, sensitivity and precision frontiers of particle physics. By mid January 1984, when this first run ended, the fixed target experimentalist's view of the accelerator was back to what it had always been - the black box from which the beam emerged. That attitude was a clear sign of success. The run was followed immediately by 800 GeV/c operations beginning April 1, 1984 with the same 5 beam lines running - two of them with new experiments.

There have been 43 experiments in the Tevatron fixed target program. Many of these are better described as experimental programs, each with a broad range of physics goals and results, and more than 100 collaborating physicists and engineers. The results of this program are threefold: (1) new technologies in accelerators, beams and detectors which advanced the state of the art; (2) new experimental results published in the refereed physics journals; and (3) newly trained scientists who are both the next generation of particle physicists and an important part of the scientific, technical and educational backbone of the country as a whole. In this book we compile these results. There are sections from each experiment including what their physics goals and results were, what papers were published, and which students have received degrees.

Summaries of these results from the program as a whole are quite interesting, but the physics results from this program are too broad to summarize globally. The most important of the results appear in later sections of this booklet.

Experimental HEP Publications 1990-99



The papers and degrees lend themselves to a more quantitative programmatic analysis. We have counted the experimental papers resulting from all of the US laboratories over the decade of the 1990's which have been published in the major refereed journals. Of the 895 such papers, 294, one third, have come from the Tevatron fixed target program. We have counted a total 465 degrees, 381 doctorates and 84 masters degrees, earned by students from 104 universities based upon work done in the Tevatron fixed target program. For comparison, the Fermilab collider program, which started a few years later, has produced 310 advanced degrees. The international character of the fixed target program is evident when the advanced degrees are sorted by state and country. As the table below shows, universities in 30 of the US states and territories as well as 17 foreign countries gave advanced degrees for work done in this Fermilab program. Among the top 10 are Japan, Italy, Brazil and Germany. One third of all the advanced degrees were given by foreign universities.

	MS	PhD	Tot		MS	PhD	Tot
Belgium	-	1	1	Brussels University	-	1	1
Brazil	8	13	21	Centro Brasileiro de Pesquisas Fisicas	5	8	13
				Federal University of Rio de Janeiro	-	1	1
				Pontificia Universidade Catolica Rio de Janeiro	1	-	1
				State University of Campinas	-	1	1
				University of Sao Paulo	2	3	5
California	-	26	26	Stanford University	-	1	1
				University of California at Berkeley	-	3	3
				University of California at Davis	-	7	7
				University of California at Los Angeles	-	5	5
				University of California at San Diego	-	1	1
				University of California at Santa Barbara	-	7	7
				University of California at Santa Cruz	-	2	2
Canada	2	7	9	McGill University	2	3	5
				University of Toronto	-	4	4
Colorado	-	11	11	University of Colorado	-	11	11
Connecticut	-	7	7	Yale University	-	7	7
England	-	1	1	Imperial College - London	-	1	1
Florida	-	3	3	Florida State University	-	3	3
France	-	3	3	University of Paris - Sud	-	3	3
Georgia	-	1	1	Georgia State University	-	1	1
Germany	6	11	17	Aachen University	-	1	1
				Max-Planck-Institut Fur Kernphysik	6	5	11
				Technischen Universitaat Munich	-	2	2
				University of Freiberg	-	2	2
				Wuppertal University	-	1	1
Greece	-	5	5	University of Athens	-	5	5
Hawaii	-	1	1	University of Hawaii	-	1	1
Illinois	5	41	46	Illinois Institute of Technology	-	2	2
				Northern Illinois University	5	-	5
				Northwestern University	-	7	7
				University of Chicago	-	19	19
				University of Illinois at Chicago Circle	-	6	6
				University of Illinois at Urbana-Champaign	-	7	7
India	-	3	3	University of Delhi	-	3	3
Indiana	3	16	19	Ball State University	2	-	1
				Indiana University	1	5	6
				Notre Dame University	-	11	11
Iowa	3	6	9	University of Iowa	3	6	9
Israel	2	2	4	Tel Aviv University	2	2	4
Italy	7	21	28	University of Bari	-	1	1
				University of Lecce	2	-	2
				University of Milano	4	9	13
				University of Pavia	1	10	11
				University of Roma	-	1	1
Japan	33	16	49	Aichi University of Education	1	-	1
				Kobe University	3	2	5
				Kyoto University	-	5	5
				Nagoya University	4	2	6
				Osaka City University	4	1	5
				Osaka University	8	4	12

	MS	PhD	Tot		MS	PhD	Tot
				Toho University	5	2	7
				Utsunomiya University	8	-	8
Kansas	-	3	3	Kansas State University	-	2	2
				University Kansas	-	1	1
Korea	2	4	6	Korea University	2	4	6
Maryland	-	5	5	University of Maryland	-	5	5
Massachusetts	-	23	23	Harvard University	-	4	4
				Massachusetts Institute of Technology	-	4	4
				Northeastern University	-	8	8
				Tufts University	-	5	5
				University Massachusetts at Amherst	-	2	2
Mexico	4	6	10	Cinvestav	1	5	6
				Universidad Autonoma de San Luis Potosi	2	-	2
				Universidad de Puebla	1	-	1
				University of Guanajuato	-	1	1
Michigan	-	16	16	Michigan State University	-	8	8
				University of Michigan	-	8	8
Minnesota	-	7	7	University of Minnesota	-	7	7
Mississippi	-	1	1	University of Mississippi	-	1	1
Missouri	-	1	1	University of Missouri	-	1	1
Netherlands	-	1	1	Universiteit Antwerpen	-	1	1
New Jersey	-	10	10	Princeton University	-	4	4
				Rutgers University	-	6	6
New Mexico	-	2	2	New Mexico State University	-	2	2
New York	1	32	33	Columbia University	-	16	16
				State University of New York at Albany	-	1	1
				State University of New York at Stony Brook	-	3	3
				University of Rochester	1	12	13
North Carolina	-	5	5	Duke University	-	5	5
Ohio	-	11	11	Case Western Reserve University	-	1	1
				Ohio State University	-	5	5
				University of Cincinnati	-	5	5
Oklahoma	-	1	1	University of Oklahoma	-	1	1
Pennsylvania	-	15	15	Carnegie Mellon University	-	2	2
				Carnegie Melon University	-	3	3
				Lehigh University	-	1	1
				Pennsylvania State University	-	2	2
				University of Pennsylvania	-	3	3
				University of Pittsburgh	-	4	4
Puerto Rico	6	-	6	University of Puerto Rico	6	-	6
Russia	-	1	1	Moscow State University	-	1	1
South Carolina	-	1	1	University of South Carolina	-	1	1
Switzerland	-	1	1	University of Geneva	-	1	1
Taiwan	-	1	1	National Cheng-KunUniversity	-	1	1
Tennessee	-	6	6	University of Tennessee	-	4	4
				Vanderbilt University	-	2	2
Texas	2	13	15	Rice University	2	10	12
				Texas A&M University	-	1	1
				University of Houston	-	1	1
				University of Texas at Austin	-	1	1
Virginia	-	5	5	University of Virginia	-	5	5
Washington	-	7	7	University of Washington	-	7	7
Wisconsin	-	8	8	University of Wisconsin	-	8	8

These numbers are incomplete. While data taking with 800 GeV/c beam ended in January 2000, analysis from some of the largest experiment programs will continue for several more years. There will probably be more than 50 additional papers published and a similar number of students graduated before this program will be truly complete.

Milestones denote progress on a journey. Now, seventeen years after the first beam was delivered, we have gathered to celebrate the milestone of the end of fixed target runs with the Tevatron. We will look today at where we have been and where we will be going next. The physics results from the Tevatron fixed target program have helped form our present understanding of nature and shaped some of the directions for future research. The technological advances we have made have already found their way into our new Main Injector and other accelerators, as well as current and planned future generations of detectors. The scientists who were trained in the Tevatron fixed target program, either as graduate students or in more senior positions, form the core of the upcoming Main Injector fixed target program. That program is already digging holes in the ground for future neutrino experiments, new experiments but with the same types of beams that began our fixed target programs in the past.

We have come today not to bury fixed target physics or simply to celebrate it, but to remind ourselves of the exceptional progress we have made, and to begin again with a next generation of Fermilab fixed target experiments. As with Mark Anthony, we'll sneak in a little praise for the old program as well.

INVESTIGATING QCD AT FIXED TARGET ENERGIES
SECTION 3

Table of Contents

3. INVESTIGATING QCD AT FIXED TARGET ENERGIES

3.1 INTRODUCTION

Quantum Chromodynamics (QCD) describes the strong force that binds quarks within hadrons, the class of strongly interacting particles that includes the proton and the neutron. QCD has some similarities to QED (Quantum Electrodynamics), the quantum theory of the electromagnetic force. However, there are substantial differences that affect our ability to make calculations using these theories. Calculations based on QED are the most accurate in all of physics, while those involving QCD can often only be approximated. These differences arise partly from the charge structure of the two theories. QED has a single charge, the familiar electric charge. QCD has three types of charge, referred to as "colors" (the "Chromo" in Chromodynamics), which combine to yield neutral (colorless) states in analogy to the way three primary colors combine to create white, or colorless, light.

As a consequence of the existence of three types of QCD charge, instead of being mediated by a single massless particle (the photon of QED), QCD involves eight massless intermediaries, known as gluons (that "glue" quarks together). Moreover, while a photon is electrically neutral and does not interact directly with other photons, gluons carry color charge and interact strongly with one another.

The QCD force is about 100 times stronger than QED, and includes more complicated interactions than QED (because of the gluon-gluon interaction). In addition, although the QED force between charged particles becomes weaker with distance, at typical intra-quark distances in hadrons the QCD force between quarks is approximately constant. Thus the energy in the color field increases linearly with the distance between the quarks (until there is enough energy in the field to create quark-antiquark pairs). This property leads to the confinement of quarks within ordinary (colorless) matter, enabling the weaker QED force to dominate on atomic scales (with the happy results that atoms have the structure they do and that we exist to comprehend such things as QED and QCD).

Quark confinement also makes QCD more difficult to study at fixed target energies. This follows from the uncertainty principle, distance and momentum measurements are inversely related (large distances result in small amounts of momentum being transferred between interacting particles, at small distances large amounts of momentum can be exchanged). Thus, a mathematical technique known as perturbation theory, which is most reliable under circumstances in which an interaction is weak, can be employed to carry out very precise QED calculations in the kinematic regime of large distances and low momentum transfers. These conditions are relatively easy to access at fixed target energies. In contrast, the QCD force is weak only at small distances and large momentum transfers, a regime most easily reached in the highly energetic collisions characteristic of collider interactions.

Studying QCD at fixed target energies must necessarily involve experiments that address simple interactions that can be calculated reasonably accurately at lower energies, or that focus on processes that benefit from the increased precision of very high event rates achieved in fixed target experiments.

3.2 E609 - THE STRUCTURE OF HIGH P_T HADRONIC INTERACTIONS

Argonne National Laboratory, Fermilab, Lehigh University, University of Pennsylvania, Rice University, University of Wisconsin – Madison

Following the discovery of quarks in deep inelastic scattering of electrons on protons, Bjorken and associates predicted that in hadron-hadron collisions one could expect to see hadron jets at high transverse momentum, with the properties of approximate coplanarity and approximate balance of transverse momentum, associated with a 2-body collision of constituents of the colliding hadrons. In order to search for such jet pairs, and if found, to study the interactions giving rise to parton-parton scattering within nucleons and mesons, experiment E395 and its successor E609 were designed.

In order to detect multiparticle high-p_T "jets", collaborators designed and developed the first 2-dimensional segmented calorimeter detector, and introduced the wave-shifter readout technique. E395/609 detected jet pairs of approximately the predicted properties. They measured the magnitude of parton-parton scattering, the difference in momentum fractions carried by quarks in the pion and the proton (the pion has a pair of quarks, the proton has three quarks), the parton transverse momentum in the colliding hadrons, and other features of parton scattering.

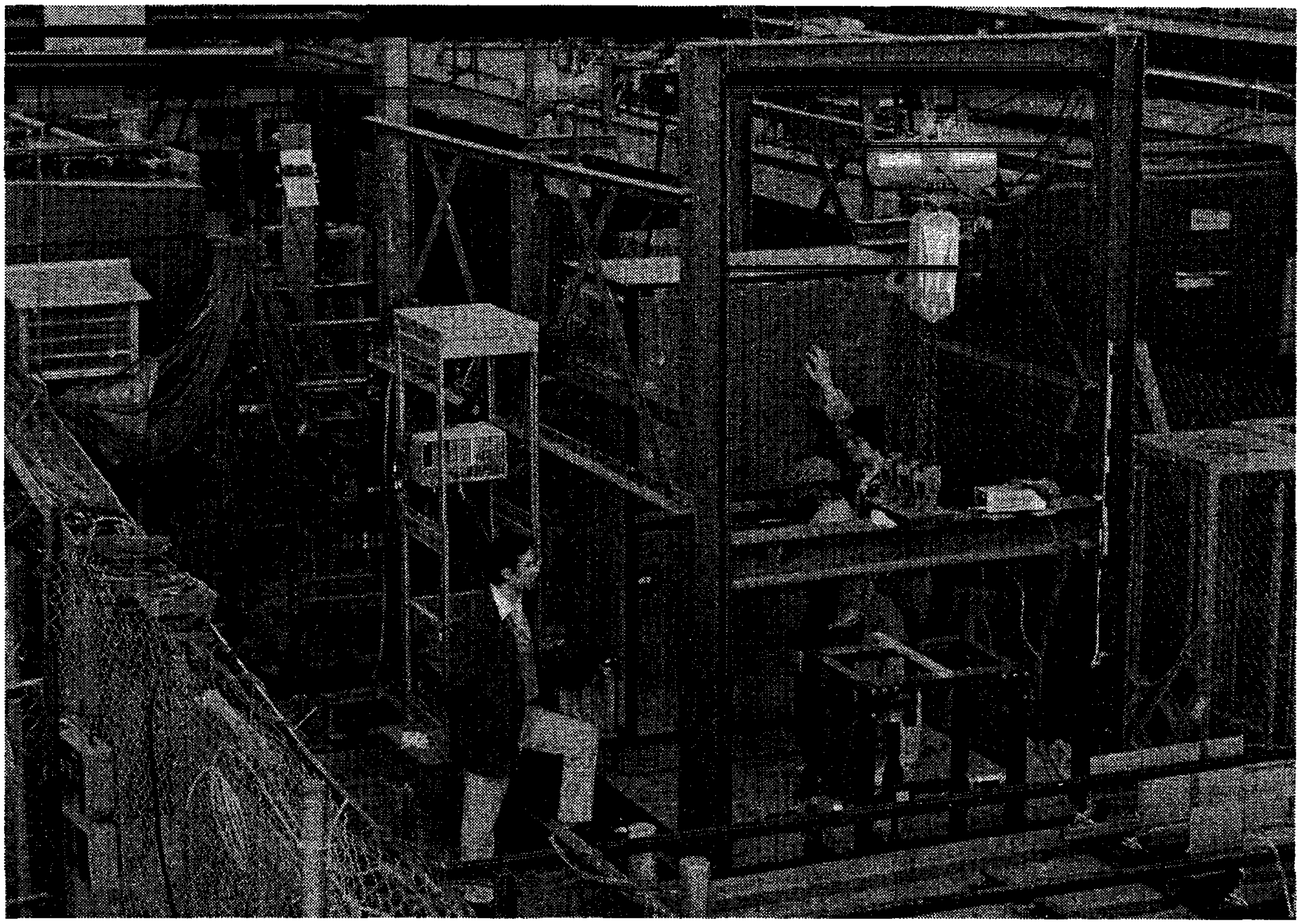
E609 Degree Recipients

Jack Gerald Fleischman	Ph.D.	University of Pennsylvania
Kenneth Johns	Ph.D.	Rice University
Clara Kuehn	Ph.D.	University of Wisconsin
Martin Richard Marcin	Ph.D.	Rice University
Robert Christopher Moore	Ph.D.	Rice University
Charles Joseph Naudet	Ph.D.	Rice University
Kenneth Scott Nelson	Ph.D.	University of Wisconsin
James Allen Rice	Ph.D.	Rice University
Hsiuan-Jeng Shih	Ph.D.	Lehigh University

E609 Publications

Evidence that High-p_T Jet Pairs Give Direct Information on Parton-Parton Scattering., M.D. Corcoran, *et al.*, Phys. Rev. Lett. **44**, 514 (1980).
Comparison of High-p_T Events Produced by Pions and Protons., M.D. Corcoran, *et al.*, Phys. Rev. Lett. **41**, 9, (1978).

A Study of Parton Transverse Momentum Using Jets from Hadron Interactions., M.D. Corcoran, *et al.,* Phys. Rev. **D21**, 641 (1980).
Measurement of the Single Jet Invariant Cross-Section at Fermilab., L.R. Cormell, *et al.*, Phys. Lett. **B150**, 322 (1985).
Measurement of the DiJet Cross-Section in 400 GeV p p Interactions,. M.W. Arenton, *et al.*, Phys. Rev. **D31**, 984 (1985).
Ev*idence for Higher Twist Effects in Hard* πp *Collisions at 200 GeV/c.*, C. Naudet, *et al.*, Phys. Rev. Lett. **56**, 808 (1986)
Measurement of Massive $\Lambda K_s^o \pi^+ \pi^+ \pi^- \pi^-$ *Events above 5 GeV/c-squared.*, M.W. Arenton, *et al.*, Nucl. Phys. **B274**, 707 (1986).
Invariant Cross Section at $\sqrt{s} = 28$ *GeV for Coplanar High-pT Clusters Selected by a Hardware Trigger.*, K.S. Nelson, *et al.*, Nucl. Phys. **B294**, 1022 (1987).
Jet Production from Nuclei at 400 GeV/c., H.E. Miettinen, *et al.*, Phys. Lett. **B207**, 222 (1988).
Energy Flow in Hard Proton-Nucleus Collisions at 400 GeV/c., R.C. Moore, *et al.*, Phys. Lett. **B244**, 347 (1990).
Evidence for Multiple Scattering of High-Energy Partons in Nuclei., M.D. Corcoran, *et al.*, Phys. Lett. **B259**, 209 (1991).
Anomalous Nuclear Enhancements in Hard p A collisions at Fermilab Energies., T. Fields, *et al.*, Nucl. Phys. **A544**, 565 (1991).
Experimental Information on the Pion Gluon Distribution Function., A. Bordner, et al., Z. Phys. **C72**, 249 (1996).



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Measurement of the dijet cross section in 400-GeV/c pp interactions

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[b]Fermilab, Batavia, Illinois 60510
[c]Lehigh University, Bethlehem, Pennsylvania 18015
[d]University of Michigan, Ann Arbor, Michigan 48109
[e]University of Pennsylvania, Philadelphia, Pennsylvania 19104
[f]Rice University, Houston, Texas 77001
[g]University of Wisconsin, Madison, Wisconsin 53706

(Received 9 April 1984)

The invariant cross section for production of jet pairs in 400-GeV/c pp interactions has been measured as a function of p_T in the p_T range 4 to 9 GeV/c. The results are in good agreement with predictions of a perturbative QCD model. Details of the experiment and the procedures used to extract the jet signal are given.

I. INTRODUCTION

The study of jet production in hadronic interactions has been motivated by the expectation that the jets directly reflect the underlying parton-parton scattering. Early studies of high-p_T single particles have provided results that, while giving information on the nature of the hard scattering process, do not directly measure the parton scattering cross section.[1] Recently, however, clear evidence for jet production in hadronic interactions has been observed. This evidence is visually striking at the 540-GeV center-of-mass energy of the CERN SPS collider,[2,3] and is also clear at the highest CERN ISR energies.[4] At the lower energies of Fermilab and SPS fixed-target experiments the situation is more complicated.[5,6] Nevertheless, as we have shown in previous papers,[7] jets can definitely be seen at these lower energies. Here we extend and refine our analysis in order to determine the invariant cross section for the production of jet pairs.

This article is organized as follows. First the experimental apparatus and its calibration are described. Then we proceed to discuss the analysis, the main parts of which are the methods for determining the jet signal and the calculations of the trigger efficiency. We then present the results on the dijet cross section and compare them with predictions of a simple theoretical model. More detailed discussions of resolution questions and of procedures for estimating the background are given in the Appendices.

II. EXPERIMENTAL METHOD

A plan view of experiment E-609, located in the M6 beam line at Fermilab, is shown in Fig. 1. The 400-GeV/c proton beam was incident on a 45-cm liquid hydrogen target. Since rare processes such as high-p_T jet production may be faked by (or even obscured by) accidental coincidences of more common events, special precautions were taken to ensure that only a single beam particle entered the target. A dE/dx counter in the beam rejected cases with more than one beam particle in the same rf bucket. Pile-up circuitry rejected beam particles with a second beam particle within ± 110 ns, the width of the analog-to-digital-converter (ADC) gates. A wall of veto counters embedded in the massive iron shield upstream of the apparatus rejected events accompanied by muons. The average beam flux eligible to make events after these requirements was 1.5×10^5 per 1-s spill. The total integrated luminosity used in the results reported here was 7.5×10^{33} cm^{-2}.

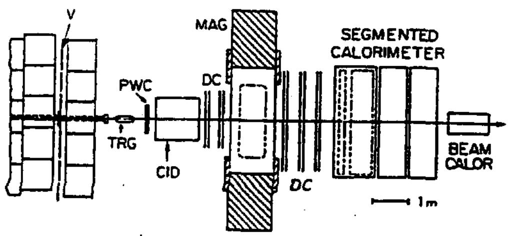

FIG. 1. Plan view of the E-609 experiment. V, veto counters; TRG, hydrogen target; DC, drift chambers.

Following the target was a magnetic spectrometer consisting of a 1×3-m aperture analyzing magnet surrounded by planes of proportional and drift chambers. The magnet was operated with a low transverse-momentum kick of 100 MeV/c to avoid complicating the geometrical triggers (described below) which assumed straight-line trajectories. In the present analysis the charged-particle tracking has been used only to determine the position of the production vertex to separate events occurring in the target hydrogen from background events produced else-

3.3 E683 - PHOTOPRODUCTION OF HIGH P_T JETS

Ball State, Fermilab, Iowa, Maryland, Michigan, Rice, Vanderbilt

E683 was the last in a series of experiments designed to study jet production in proton-proton, pion-proton, and photon-proton collisions. Some of the earlier experiments (E395, E609) were done at beam energies of 400 GeV, before the Tevatron era. Experiments done by other groups (E557) also studied jet production at Tevatron energies. To understand the context of these experiments, one needs to understand that in the early 80's the existence of parton scattering and jet production was far from established. Earlier claims of the observation of jets in limited-solid-angle detectors had been quite controversial. It took the large-acceptance fixed-target experiments (E609 and E557) and especially the advent of the proton-antiproton colliders to firmly establish the existence of parton scattering and jet production.

E683 studied the photoproduction of high transverse momentum jets in the Wide Band Photon beam, with a tagged photon beam ranging in energy from 150 GeV to 350 GeV. For comparison and calibration, E683 also took some data with a pion beam of mean energy 250 GeV. Photoproduction is interesting because, due to its much harder parton distribution function (compared to protons or pions), the photon delivers a much larger fraction of the available CM energy to the hard scattering process, leaving less energy in the spectator system. Thus, photoproduction gives a cleaner jet signal compared to hadroproduction. The emergence of the jet signal was indeed clearly observed in E683 in photon-proton collisions, even with an unbiased trigger. The jet signal was much cleaner for photon-initiated events than for pion-initiated events.

An expectation from leading order QCD theoretical calculations, is that there should be a sharp distinction between the point-like interaction of the photon (the "direct" process) and its pion-like interaction (the "resolved" process). In higher order QCD, the distinction between these two processes is blurred, and in fact E683 did not observe a separation of the photoproduced jet events into these two distinct classes.

In addition to a proton target, E683 studied nuclear effects. Uncertainty principle arguments predict that hadronization occurs outside the nucleus. The parton can rescatter off nuclear matter as it exits the nucleus. Evidence for such rescattering effects had been seen in p-nucleus interactions in earlier experiments, and these effects were also quite evident in the photon-nucleus and pion-nucleus data from E683.

E683 Degree Recipients

Drew Alton	M.S.	Ball State University
Bill Davis	M.S.	Ball State University
Chafiq Halli	Ph.D.	University of Maryland
Don Lincoln	Ph.D.	Rice University
Gregory Peter Morrow	Ph.D.	Rice University
Donna Lynne Naples	Ph.D.	University of Maryland
Michael M. Traynor	Ph.D.	Rice University

E683 Publications

The Emergence of Jet Dominance in gamma-p Interactions at Fixed Target Energies., D. Alton, *et al.,* Phys. Rev. **D56**, 5301 (1997).
Observation of Jet Production by Real Photons., D. Adams, *et al.,* Phys. Rev. Lett. **72,** 2337 (1994).
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Observation of Jet Production by Real Photons

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Interactions of high energy photons on a hydrogen target have been studied using a large acceptance segmented calorimeter. The event topology clearly shows the production of dijet final states as predicted by perturbative QCD. The energy flow in the photon (forward) direction is compared to Monte Carlo expectations and to that produced in πp interactions.

PACS numbers: 13.87.Ce, 12.38.Qk, 13.60.Hb

Jets arise from the fragmentation of partons in hard scattering processes. Jets have been observed in many experiments in hadron-hadron interactions [1] as well as in deep inelastic lepton-hadron interactions [2] and e^+e^- annihilations [3]. Single high p_t hadrons and energy flow distributions have been studied in earlier, lower energy, photoproduction experiments [4], but until now no observation has been made of jet production by a real photon beam. Recent results from the DESY ep collider HERA show evidence for hard scattering in quasireal-photon-proton interactions [5]. In this Letter we report the first observation of jets produced by a real photon beam incident on a proton target.

In low momentum-transfer processes, photon interactions leading to hadronic final states can be described by the vector-dominance model (VDM), in which photons act like vector mesons [6]. But at high momentum transfer (high p_t), other processes are expected to dominate [7]. These include the direct coupling contribution, in which the photon couples directly into the hard scattering process, and the so-called "resolved" photon contributions, in which the photon first dissociates into a quark-antiquark pair. In the direct process, the photon disappears, leaving no spectator remnant. The final state consists of three jets: two high-p_t jets and a soft target jet. In both the VDM and resolved contributions, the photon has a spectator remnant, thus producing a four-jet final state. When higher-order QCD diagrams are considered, there is no sharp distinction between the direct and resolved processes, but with well-defined experimental cuts, it might be possible to divide events into categories which approximate the Born-level contributions.

We have observed the photoproduction of high p_t jets in experiment E683 in the wide band photon beam at Fermilab, which has incident tagged photon energies ranging from 50 to 400 GeV. Jets have been observed in the p_t range of 3–9 GeV/c. Photons were produced by bremsstrahlung from a secondary electron beam incident on a lead radiator which was 20% of a radiation length. The incoming electron beam had a mean momentum of 310 GeV/c, and an rms momentum spread of $\pm 15\%$. The energy of the incoming electrons was tagged by an array of silicon microstrip detectors. After the electron radiated, sweeper magnets bent it into an array of shower counters which measured its final energy. The photon energy is taken to be the difference between the incoming and outgoing electron energies, and is known to $\pm 2\%$. Monte Carlo simulations of the beam indicate that our trigger selects events in which little multiple bremsstrahlung has occurred, resulting in less than a 5% overestimate of the photon energy. We have not corrected for this effect.

The experimental apparatus is shown in Fig. 1. Two scintillation counters upstream of the target vetoed charged particles from photons which had converted in material upstream. A counter immediately downstream of the target required at least one charged particle exiting the target. Two planes of scintillator hodoscopes vetoed events which were accompanied by an off-axis muon. This analysis is based on information from a highly segmented electromagnetic and hadronic main calorimeter (MCAL), covering a laboratory pseudorapidity (η) range from 2.6 to 4.9, corresponding to laboratory polar angles (θ_L) of 0.8° to 8.5°. The MCAL has been described in detail elsewhere [8]. It consisted of 132 towers of lead-scintillator and steel-scintillator sampling calorimetry,

3.4 E690 - STUDY OF CHARM AND BOTTOM PRODUCTION

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This experiment studies proton diffraction, pp→pX, using 800 GeV protons scattering from liquid hydrogen, measuring a diffracted forward proton in a forward beam spectrometer, and looking at the recoil system X in a magnetic spectrometer. The detector and its data acquisition system were designed to tolerate interaction rates on the order of 1 MHz, reading 100K events per second into a pipelined hardware processor, and ultimately recording on tape more than 10K events per second of beam. In three months of running, E690 recorded more than 5 billion events, with periods of sustained running yielding 200K events per spill. The trigger required the coincidence of an incoming beam particle, an outgoing beam particle within the acceptance of the forward spectrometer but scattered out of the small beam envelope, and at least one particle in the magnetic spectrometer.

The tracks were reconstructed with the hardware processor after the run, writing all raw data and track information for every event, and selecting candidates with momentum balance for a secondary output. All events were then processed through a vertex reconstruction program that reconstructed every event in as much detail as possible, writing out everything as well as a secondary output containing candidates for complete event reconstruction, and events with identified strange particles. The data set contains a few hundred million reconstructed V^0's and approximately ten million fully reconstructed events, recorded with good resolution and a geometric acceptance that favors diffractive production of heavy particles.

Continuing analysis efforts are focusing on diffraction of heavy particles: antibaryons, strange particles, charm particles, ... and on particle spectroscopy. With high statistics for a large number of exclusive reactions, E690 can determine production cross-sections and parameters of many resonances. For example, in double Pomeron production, pp→p(M)p, there are large, clean signals for meson resonances that have been considered candidates for non-q-$\bar{q}$ mesons. For the general study of heavy particle production in diffraction, E690 expects to perform doubly inclusive measurements for a variety of heavy particles, measuring the momentum of the scattered forward proton and the momentum of a particular heavy particle type. Along with the measurements of exclusive reaction cross sections and distributions, E690 data will allow detailed modeling of diffractive production in pp interactions. These models can be compared, for example, with diffraction in deep inelastic ep scattering.

E690 Degree Recipients

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E690 Publications

Partial Wave Analysis of the Centrally Produced K_S K_S System at 800 GeV/c., M.A. Reyes, *et al.*, Phys. Rev. Lett. **81**, 4079 (1998).
Spin Parity Analysis of the Centrally Produced $K^0 K$ π System at 800 GeV/c., M. Sosa, *et al.*, Phys. Rev. Lett. **83**, 913 (1999).

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Partial Wave Analysis of the Centrally Produced $K_S K_S$ System at 800 GeV/c

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Results are presented from a partial wave analysis of a sample of centrally produced mesons in the reaction $pp \to p_{slow}(K_S K_S)p_{fast}$, with 800 GeV/$c$ protons incident on a liquid hydrogen target. The meson system is found to be predominantly S wave in the mass range between $K_S K_S$ threshold and 1.55 GeV/c^2. The $f_0(1500)$ is observed in this region. Above 1.55 GeV/c^2 two solutions are possible, one with mainly S wave and another with mainly D wave. This ambiguity prevents a unique determination of the spin of the $f_J(1710)$ meson. [S0031-9007(98)07609-1]

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Significant theoretical progress has been made recently with two separate lattice gauge calculations of the lowest lying scalar glueball [1]. The two calculated masses are 1550 ± 95 MeV/c^2 and 1740 ± 71 MeV/c^2. The leading experimental candidates are the $f_0(1500)$ and the $f_J(1710)$. The $f_0(1500)$ was first observed in $\pi^- p$ interactions [2]. Its existence was beautifully confirmed, and several decay branching ratios were measured by the Crystal Barrel Collaboration [3]. Amsler and Close [4] have pointed out that the values of these branching ratios make it unlikely that the $f_0(1500)$ is a $q\bar{q}$ meson. If the $f_0(1500)$ is a glueball, then its production may be favored in doubly diffractive hadronic interactions. In this paper, we report the observation of the $f_0(1500)$ in central production in the doubly diffractive reaction,

$$pp \to p_{slow}(K_S K_S)p_{fast}, \qquad K_S \to \pi^+\pi^-. \quad (1)$$

The advantage of the $K_S K_S$ system over K^+K^- is that for two identical bosons only states with $J^{PC} = (\text{even})^{++}$ are allowed.

The results presented here are based on an analysis of 10% of the 5×10^9 events recorded by Fermilab E690 during Fermilab's 1991 fixed target run. The E690 apparatus consisted of a high rate, open geometry multiparticle spectrometer (Fig. 1) used to measure the target system (T) in $pp \to p_{fast}(T)$ reactions, and a beam spectrometer system used to measure the incident 800 GeV/c beam and scattered proton. A liquid hydrogen target was located just upstream of the multiparticle spectrometer. The target was surrounded by a segmented lead-scintillator "veto counter," which was used to detect the presence of charged or neutral particles outside the aperture of the multiparticle spectrometer [5].

Final state (1) was selected by requiring a primary vertex in the LH_2 target with two K_S, an incoming beam track, and a fast forward proton. No direct measurement was made of the slow proton p_{slow}, and no direct particle identification was used. The target veto system was used to reject events with more than a missing proton. Events were accepted when no veto counter was on, or only one veto counter was on, and the missing p_t pointed to it.

The missing mass squared seen in Fig. 2a shows a clear proton peak with little background. Figure 2b shows the uncorrected x_F distribution for the $K_S K_S$ system. The distribution is not symmetric about $x_F = 0$ because the detection efficiency and momentum resolution of the multiparticle spectrometer decreased rapidly for high energy particles produced in the forward direction in the pp center of mass system. Figure 2c shows the $\pi^+\pi^-$ invariant mass distribution; the arrows indicate the cuts used. In all plots the selected events are shaded. With this selection, the minimum rapidity gap between p_{slow} and the $K_S K_S$ system is 1.2 units. The rapidity gap between the meson system and p_{fast} is greater than 3.7 units for all events.

In the selected events, the three momentum of p_{slow} and the longitudinal momentum of p_{fast} were calculated

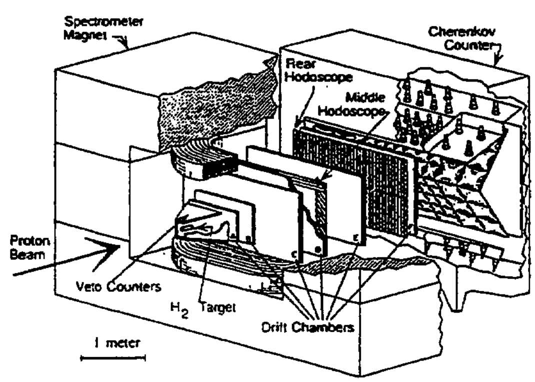

FIG. 1. E690 multiparticle spectrometer.

3.5 E704 - EXPERIMENTS WITH THE POLARIZED BEAM FACILITY

ANL, Fermilab, Hiroshima (Japan), IHEP/Protvino (Russia), Iowa, Kyoto (Japan), Kyoto Education (Japan), Kyoto Sangyo (Japan), LANL, LAPP/Annecy (France), Northwestern, Univ. of Occup. & Env. Health (Japan), Rice, Saclay (France), Trieste (Italy), Udine (Italy)

E704 (and E581) had the highest energy polarized proton beam and the only polarized antiproton beam to date. A number of survey experiments and also preliminary measurements relevant to gluon spin were made before the beam was decomissioned to make way for SSC test beams. Among the experiments were spin dependent total cross sections, inclusive charged and neutral pion and eta production, spin transfer to lambdas, and spin effects in the inverse Primakoff effect. Also, polarimetry methods were developed which can be used at other accelerators. There are several experimental indications that spin effects are significant at high energy. The presence of these large effects, particularly in inclusive reactions, is investigated by measuring at high p_T and high x_F for various reactions.

E581/704 Degree Recipients

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E581/704 Publications

Analyzing-Power Measurement in Inclusive π^0 Production at High x_F., B.E. Bonner, *et al.*, Phys. Rev. Lett. **61**, 1918 (1988).
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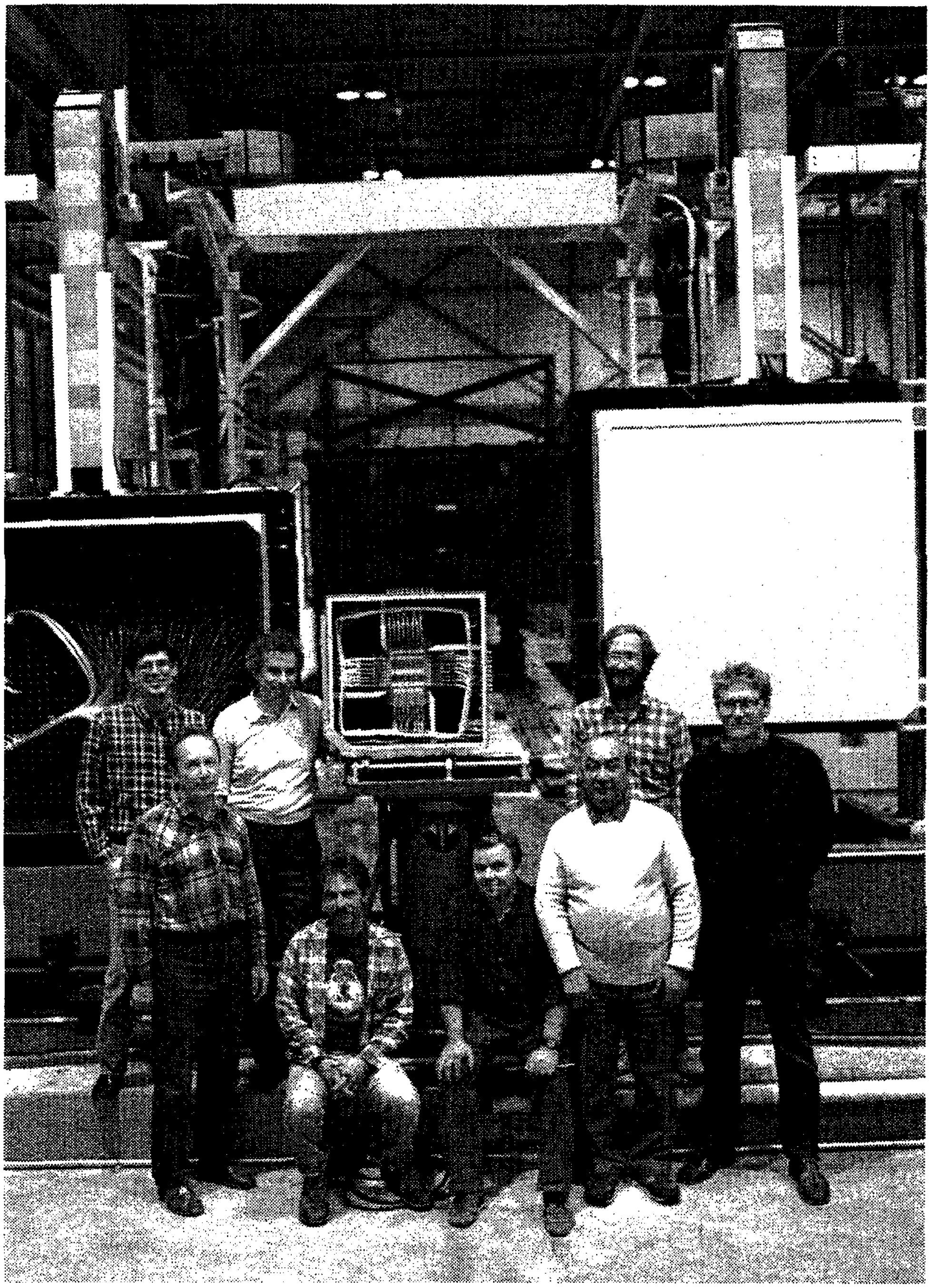

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Single-Spin Asymmetries in Inclusive Charged Pion Production by Transversely Polarized Antiprotons., A. Bravar, *et al*, Phys. Rev. Lett. **77**, 2626 (1996).
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Spin Transfer in Inclusive Lambda Production by Transversely Polarized Protons at 200 GeV/c., A. Bravar, *et al.*, Phys. Rev. Lett. **78**, 4003 (1997).

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Single-Spin Asymmetries in Inclusive Charged Pion Production by Transversely Polarized Antiprotons

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The analyzing power A_N in inclusive π^- and π^+ production has been measured with a 200 GeV/c transversely polarized antiproton beam over a wide x_F range ($0.2 \le x_F \le 0.9$) and at moderate p_T ($0.2 \le p_T \le 1.5$ GeV/c). The asymmetry A_N increases with increasing x_F from zero to large positive values for π^-'s, and decreases from zero to large negative values for π^+'s. A threshold for the onset of the asymmetry is observed about $p_T \sim 0.5$ GeV/c, below which A_N is essentially zero and above which A_N increases (decreases) with p_T for π^-'s (π^+'s) in the covered p_T range. [S0031-9007(96)01209-4]

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For the first time a high energy polarized antiproton beam was obtained at Fermilab from the parity violating decay of anti-Λ^0 hyperons [1]. Inclusive reactions measured with this beam give insight into the spin dependence of the underlying partonic processes and add new input regarding the debated question of the spin structure of polarized protons. The results from polarized lepton deep inelastic scattering [2] suggest that the overall contribution of constituent quarks to the proton helicity is small, thus implying an appreciable contribution either of sea quarks, or of gluons, or possibly of orbital angular momentum to the proton spin structure. Significant polarization effects are known to exist at medium and high energies in meson and hyperon production with hadron beams [3]: Pions produced by polarized protons show large values of the analyzing power A_N at high x_F, and hyperons produced at high x_F show large transverse polarization. A_N in inclusive pion production with polarized protons was also measured at 200 GeV/c [4,5]: The $\pi^{\pm}$ asymmetry shows an almost mirror symmetric dependence in x_F, where A_N increases with increasing x_F to large positive values for π^+ and decreases to large negative values for π^-. More recently, large negative values of A_N in inclusive Λ^0 production at 200 GeV/c and large x_F have also been published [6]. These effects appear already at relatively low values of the transverse momentum p_T ($p_T \sim 1.0$ GeV/c), where perturbative QCD is not expected to be applicable. Models were developed to explain and possibly correlate the spin observables in these processes using static SU(6) wave functions and spin dependent asymmetries introduced into

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3.6 E705 - CHARMONIUM AND DIRECT γ PRODUCTION AT 300 GEV/C

South Alabama, Arizona, Athens (Greece), Duke, Fermilab, INFN/Florence (Italy), McGill (Canada), Nanjing (PRC), Northwestern, Prairie View A&M, Shandong (PRC), SSCL, Virginia

E705, performed in the High Intensity Lab of the Proton Area, continued the study of the production of charm-anticharm bound states, also referred to as "charmonium", that had been part of the previous E537 experiment achievements. In order to study various excited states of the charm-anticharm system, the detection of dimuons was not sufficient, but it had to be complemented with the detection of high energy photons (or gamma rays), since excited states will decay into the J/ψ ground state by the emission of a photon. To this purpose, the experiment apparatus was upgraded by the inclusion of a 30-ton scintillating glass electromagnetic calorimeter, capable of measuring the energy and position of high energy gamma rays. Using very high flux pion beams, it was possible to study the processes responsible for the formation of charm-anticharm pairs, both in the ground and excited states. This in turn allowed clarification of several aspects of Quantum Chromodynamics (QCD). An unexpected result of E705 was the first and, to date, only observation of the high-energy production of an excited state of charmonium, the $^1P_1$ state, that cannot be produced directly in e^+e^- interactions, where most of charmonium spectroscopy had been studied.

E705 Degree Recipients

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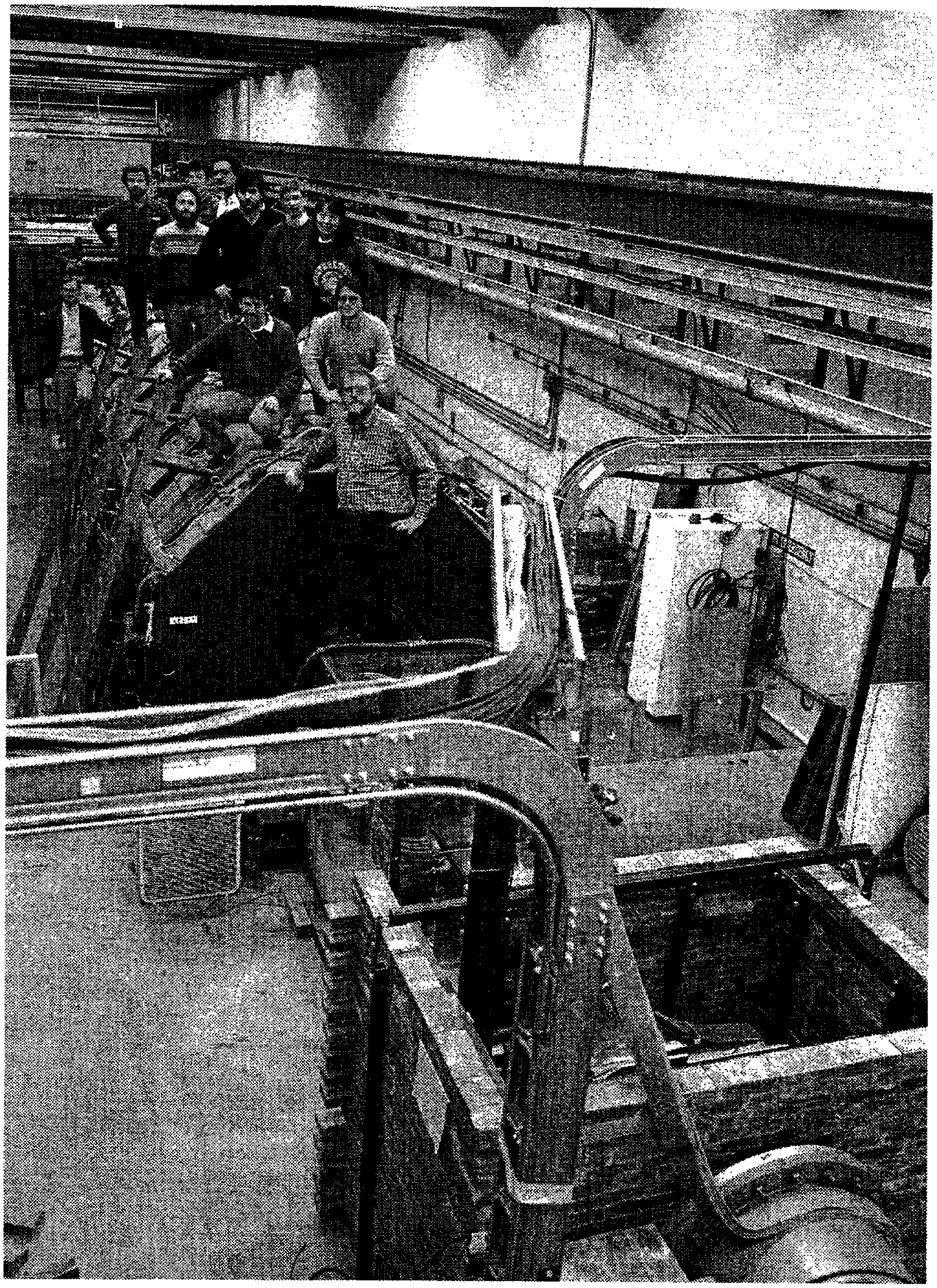
Timothy Turkington	Ph.D.	Duke University
Spiros Tzamarias	Ph.D.	University of Athens
George Zioulas	Ph.D.	McGill University



E705 Publications

Production of J/ψ via ψ' and χ_c Decay in 300 GeV/c p and $\pi^{\pm}$ Nucleon Interactions., L. Antoniazzi, *et al.*, Phys. Rev. Lett. **70**, 383 (1993).
Measurement of J/ψ and ψ' Production in 300 GeV/c Proton, Antiproton, and $\pi^{\pm}$ Interactions with Nuclei., L. Antoniazzi, *et al.*, Phys. Rev. **D46**, 4828 (1992).
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Production of χ Charmonium via 300 GeV/c p and $\pi^{\pm}$ Interactions on a Lithium Target., L. Antoniazzi, *et al.*, Phys. Rev. **D49**. 543 (1994).

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Production of J/ψ via ψ' and χ Decay in 300 GeV/c Proton- and $\pi^{\pm}$-Nucleon Interactions

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(Received 21 May 1992; revised manuscript received 21 October 1992)

The production of the χ_1 and χ_2 states of charmonium has been observed in 300 GeV/c $\pi^{\pm}N$ and pN interactions. The fraction of the total inclusive J/ψ production due to radiative χ decay has been determined to be 0.40 ± 0.04, 0.37 ± 0.03, and 0.30 ± 0.04 for the π^+, π^-, and proton data, respectively. Total cross sections for χ_1 and χ_2 production of $131\pm18\pm14$ and $188\pm30\pm21$ nb/nucleon in the 300 GeV/c π^-N interactions have been obtained. By measuring the contributions to the J/ψ production due to both ψ' and radiative χ decay, the cross sections for direct J/ψ production have been determined to be 97 ± 14, 102 ± 14, and 89 ± 12 nb/nucleon for π^+, π^-, and protons, respectively.

PACS numbers: 13.85.Ni, 13.40.Hq, 14.40.Gx

A considerable fraction [1] of the $J^{PC}=1^{--}$ J/ψ's produced in hadronic interactions results from the production of the $J^{PC}=1^{++}$ (χ_1) and 2^{++} (χ_2) states of charmonium followed by their radiative decays into $\gamma\psi$. The $J^{PC}=0^{++}$ (χ_0) state has a small branching ratio to J/ψ and is not expected to contribute appreciably to J/ψ production. In the color singlet model [2], the direct production of the J/ψ must proceed (because of conservation of angular momentum, charge conjugation, and parity) by three gluon or quark annihilation processes. Alternatively, within the color singlet model, the production of J/ψ's can proceed indirectly via production of the χ states with relatively large cross sections by the two gluon fusion, followed by the decay of the χ states into final states containing J/ψ's. A second production process is provided by the color evaporation model [3] in which the $c\bar{c}$ pair is initially produced in a colored, unbound state and the final noncolored singlet state is reached via the emission of a gluon. Therefore, an important facet of the untangling of the hadronic production mechanisms for hidden charm states is the determination of the fraction of the J/ψ production resulting from decays of the χ states. In order to ascertain the formation mechanisms for these charmonium states and, ultimately, to extract the gluon structure functions from the study of their production by various beam types, we have performed an experiment to measure the fraction of J/ψ arising from the χ radiative decays. In the process, we have determined the cross section for production of the χ states, by combining our measurement of the J/ψ cross section together with our high-statistics measurement of the ratio of $(\chi_1+\chi_2)/\psi$ production and a previous measurement [4] of the ratios of χ_1/ψ and χ_2/ψ production.

Our experiment, Fermilab E705, was performed with 300 GeV/c $\pi^{\pm}$, proton, and antiproton beams incident on a 5-cm-radius, 33-cm-long ^{7}Li target (0.21 radiation length; 0.24 and 0.175 interaction length for protons and pions, respectively) in the P-West High Intensity Laboratory at Fermilab. The beam particles were tagged with two gas Cherenkov counters operated in the threshold mode; the 300 GeV/c negative beam was 98% π^- and 2% antiprotons and the positive beam was 55% protons and 45% π^+. A small charged K contamination (estimated to be less than 6% of the total beam flux) was present in both the positive and negative beams.

The χ states produced by the four beam types were observed via their radiative decays

$$p^{\pm},\pi^{\pm}N \to \chi_1,\chi_2$$
$$\qquad\qquad \hookrightarrow J/\psi+\gamma$$
$$\qquad\qquad\qquad \hookrightarrow \mu^+\mu^-$$

3.7 E706 - DIRECT γ PRODUCTION IN HADRON INDUCED COLLISIONS

UC/Davis, Delhi (India), Fermilab, Michigan State, Northeastern, Oklahoma, Pennsylvania State, Pittsburgh, Rochester

Due to the nature of the strong interaction, reliable theoretical Quantum Chromodynamics (QCD) calculations have been difficult to achieve for most processes. However, those interactions that produce high transverse momentum particles are amenable to perturbative techniques in the context of the parton model. Perturbative QCD calculations for the production of photons emerging with high transverse momentum have been completed at next-to-leading order (NLO) in the strong coupling constant. Such direct photons provide insight into the structure of the interacting hadrons and the interactions between their constituents, and have long been viewed as an ideal probe of the gluon content of hadrons in a kinematic regime not directly accessible in most other processes.

In the Meson West beamline, experiment E706 studied high energy hadronic interactions that produce direct photons with large transverse momentum. A large, finely segmented lead and liquid argon sampling calorimeter was designed and built for this experiment. The calorimeter was used to select events based upon weighted energy deposits, and to reconstruct photon four vectors (and electron energies). The Meson West spectrometer also concurrently collected data for experiment E672, using a high-mass dimuon trigger to select events. The data from the two experiments were written to shared data tapes, and then independently analyzed.

E706 accumulated large samples of data involving hard scatters of protons at 800 GeV/c and secondary protons and pions at 500 GeV/c incident upon hydrogen, beryllium, and copper targets. The data showed that direct photons are produced at a rate that is approximately a factor of two larger than anticipated based on NLO perturbative QCD calculations. Other characteristics of the E706 data, including results on pion production at high transverse momentum as well as high-mass photon-pion pairs, provide evidence that the NLO QCD calculations do not adequately account for gluon emissions. The E706 measurement of the p_T spectrum of high transverse momentum charged D mesons provides another such indication. The results have spurred significant interest, debate, and effort in the theoretical community. The results of recent sophisticated theoretical calculations indicate that large additional contributions to direct photon production, beyond those included at NLO, can in fact be expected within the framework of QCD from the effects of initial-state gluon radiation. This re-evaluation of QCD calculations, which was motivated by the striking differences between the E706 results and NLO QCD, will yield a deeper understanding of direct photon production. Combining the consequences of these new theoretical developments and the high precision direct photon measurements from E706 into global evaluations of the parton distribution functions, should also contribute new insights into the gluon distribution.

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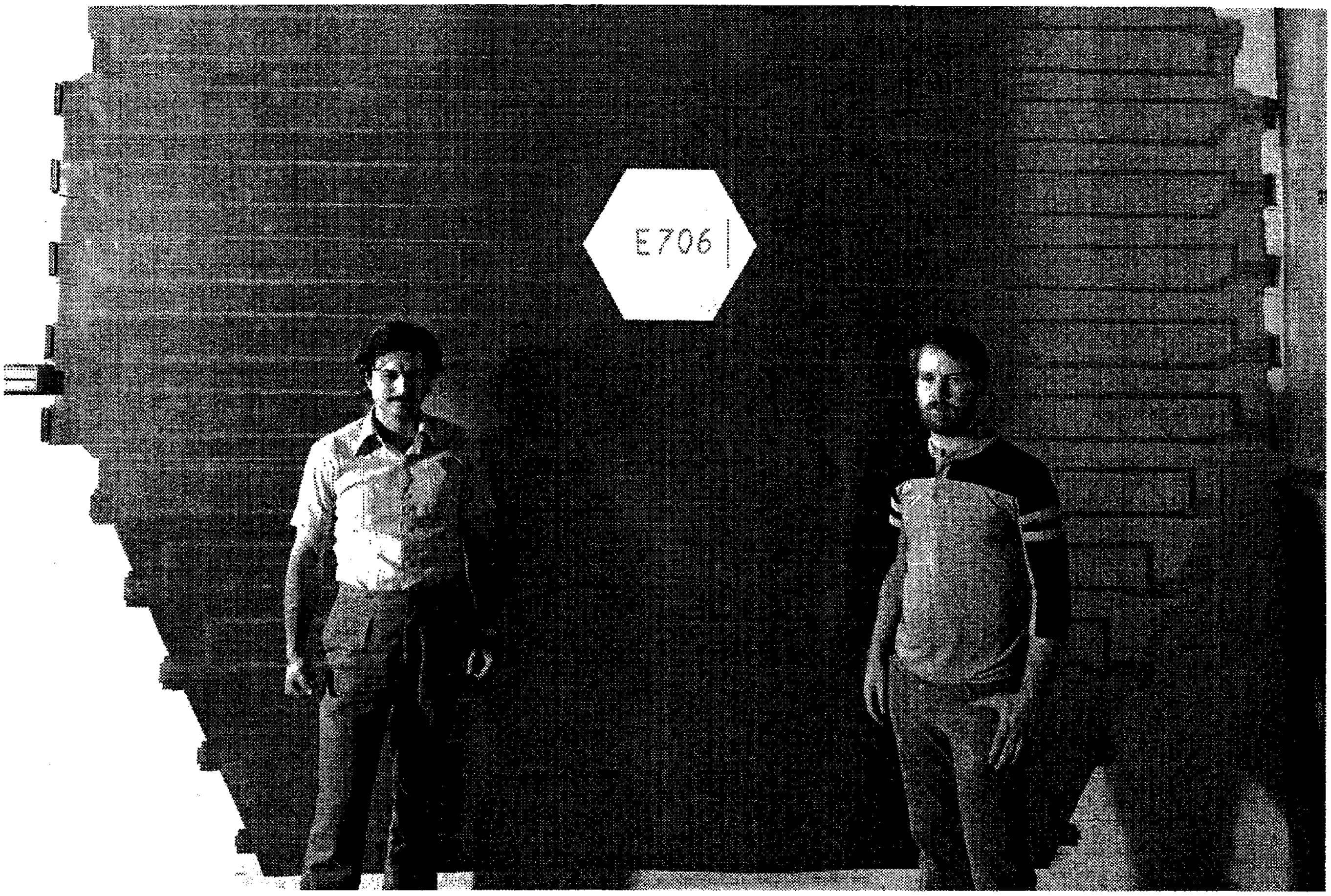

E706 Publications

Inclusive production of omega mesons at large transverse momenta in π^- Be interactions at 515 GeV/c., L. Apanasevich, *et al.*, hep-ex/0004012, submitted to Phys. Rev. **D**.
Production of J/ψ mesons in p Be collisions at 530 and 800 GeV/c., A. Gribushin, hep-ex/9910005, to be published in Phys. Rev. **D**, 1120XX (2000).
Evidence for Parton Effects in High-p_T Particle Production., L. Apanasevich, *et al.*, Phys. Rev. Lett. **81**, 2642 (1998).
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Evidence for Parton k_T Effects in High-p_T Particle Production

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(Received 24 November 1997)

Inclusive π^0 and direct-photon cross sections in the kinematic range $3.5 < p_T < 12$ GeV/c with central rapidities (y_{cm}) are presented for 530 and 800 GeV/c proton beams and a 515 GeV/c π^- beam incident on Be targets. Current next-to-leading-order perturbative QCD calculations fail to adequately describe the data for conventional choices of scales. Kinematic distributions from these hard scattering events provide evidence that the interacting partons carry significant initial-state parton transverse momentum (k_T). Incorporating these k_T effects phenomenologically greatly improves the agreement between calculations and the measured cross sections. [S0031-9007(98)07206-8]

PACS numbers: 13.85.Qk, 12.38.Qk, 13.85.Ni, 25.40.Ve

In recent years, perturbative QCD (PQCD) has been tested in a variety of strong interaction processes at short distances, and increasing attention is now being directed towards areas that may be sensitive to shortcomings in the current theoretical description [1]. The high statistics samples of hard-scattering data accumulated by Fermilab fixed-target experiment E706 provide an opportunity to probe such issues. This paper presents comparisons of PQCD calculations to our data on the production of direct photons and π^0's with large transverse momenta (p_T). Direct-photon data have long been expected to provide an accurate determination of the distributions of gluons in hadrons, especially at large longitudinal momentum fraction (x), where information has proven difficult to obtain from other measurements. Inclusive meson production at large p_T probes a different mix of hard-scattering processes and provides insight into parton fragmentation. For conventional choices of parameters, our data are not described satisfactorily by next-to-leading-order (NLO) PQCD calculations [2]. Resolving the observed discrepancies is important for improving the understanding of both parton distribution functions (PDF) and parton fragmentation functions (FF).

Several interesting aspects of QCD contributions beyond leading order (LO) can be investigated experimentally through studies of processes sensitive to transverse motion of the partons prior to the hard scatter. This k_T is presumably due to effects of hadron size (primordial k_T) as well as initial-state gluon radiation. Measurements of Drell-Yan pair production [3] and direct diphoton production [4] have demonstrated the presence of substantial effective k_T (significantly larger than can be attributed to primordial k_T), and have revealed a center-of-mass energy ($\sqrt{s}$) dependence of $\langle k_T \rangle$. (In this paper, $\langle k_T \rangle$ denotes the average magnitude of the transverse momentum vector, $|\mathbf{k}_T|$, of *each* of the two colliding partons in the initial state.) A resummation of soft-gluon emissions has recently been used to reproduce the size of the effect observed in the WA70 direct diphoton data [5]. Other data also suggest $\langle k_T \rangle$ values larger than those expected from NLO PQCD calculations. Recent comparisons of p_T spectra from charm-particle hadroproduction to NLO PQCD results provide evidence that supplemental k_T may be required to properly describe the data [6]. Likewise, it has been suggested that the observed pattern of discrepancies between data from various direct-photon experiments and results from NLO PQCD calculations could be related to k_T effects [7].

E706 is designed to measure the production of direct photons, neutral mesons, and associated particles at high p_T. The apparatus features a large lead and liquid argon electromagnetic calorimeter and a charged particle

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3.8 E711 - DIHADRON PRODUCTION

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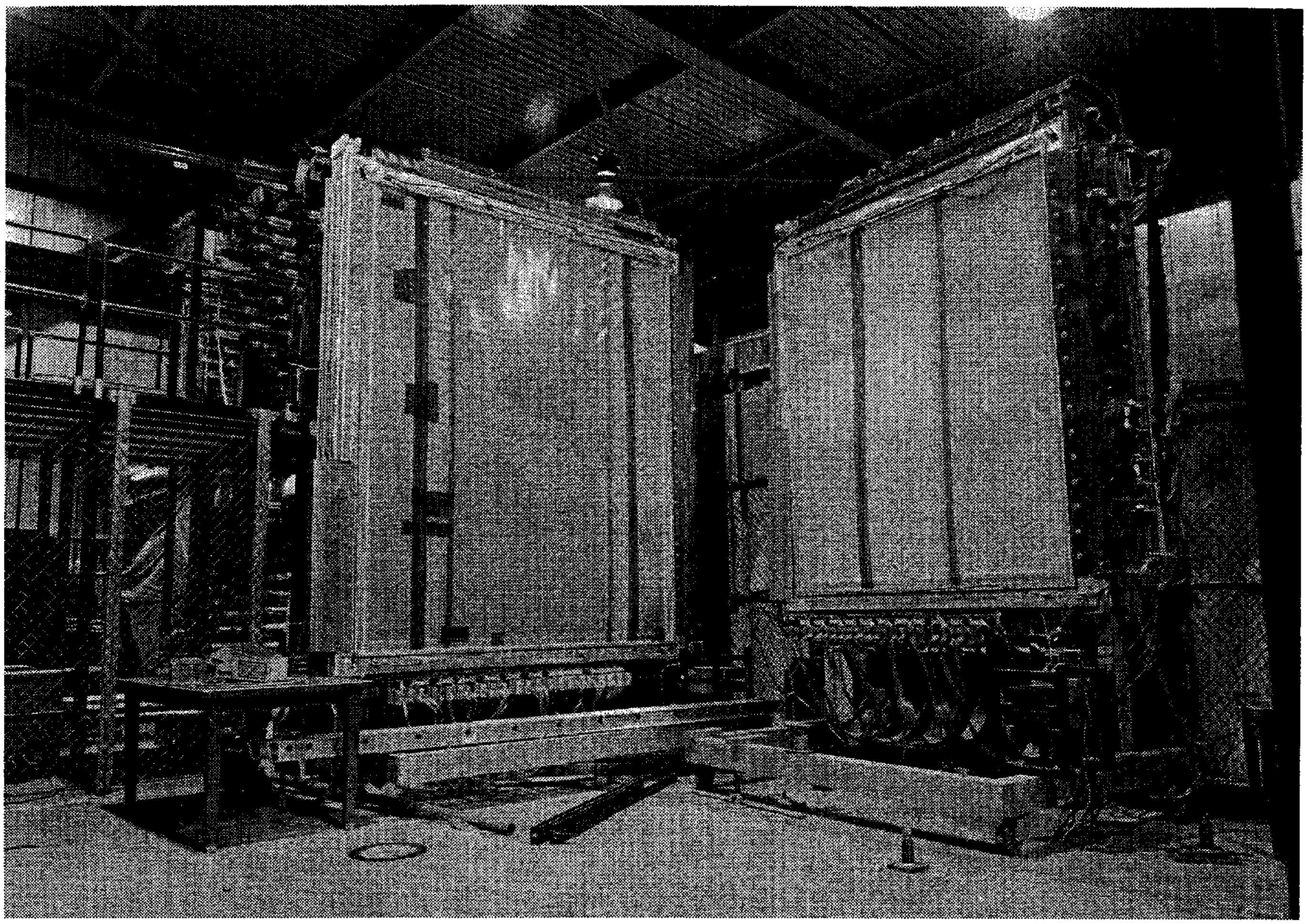
While it is generally agreed that hadronic matter is composed of quarks, some of the basic scattering amplitudes, (or properties) were not known. This experiment was designed to measure the energy, angular, and charge dependence of massive di-hadron production over a large solid angle in intense proton and pion beams. The focus of this experiment included the transverse momentum region that exploits various properties of high transverse momentum triggered events, namely identifying jet-like structures from recoiling trigger particles; the spatial correlation between the trigger particle and the hadron; and the fraction of the jet momentum carried by the leading hadron in the jet. Unlike single particle triggers, many of the characteristics of quark-quark scattering are more accurately observed using the symmetric configuration studied in this experiment. The results provided tests of QCD and other hadronic theories in hard scattering (high energy) collisions. The di-hadron production spectra provided the most direct method of measuring the energy, angular and charge dependence of the sub-constituent quark-quark scattering mechanism.

Using a number of different nuclear targets, scattering characteristics were shown to vary linearly with atomic weight, for various charge states. It was also shown that the angular distributions were also independent of the target type, and showed a small dependence on charge, thus indicating in general that the data agreed with previous measurements for other energy ranges, and with QCD calculations.

Another important result of the experiment was finding that the average fraction of the jet momentum carried by the leading hadron in that jet was independent of whether the event had a single jet or two jets, and independent of the target type. These results were consistent with QCD theoretical model predictions. In general, these studies suggest that many processes, at the level of quarks, are not affected by interactions taking place at the nuclear level. Also, at these energies, measured characteristics including the angular and charge dependencies are described well by the QCD-parton model.



E711 Degree Recipients

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Kathleen Ruth Turner Streets	Ph.D.	Florida State University
Herman Brenner White Jr.	Ph.D.	Florida State University

E711 Publication:

Atomic Weight Dependence of the Production of Hadron Pairs by 800 GeV/c Protons on Nuclear Targets., K. Streets, *et al.*, Phys. Rev. Lett. **66**, 864 (1991).
Average Fraction of Jet Momentum Carried by High p_T Hadrons., G. Boca, *et al.*, Z. Phys. **C49**, 543 (1991).
Massive Hadron Pair Production by 800 GeV/c Protons on Nuclear Targets., H.B. White, *et al.*, Phys. Rev. **D48**, 3996 (1993).

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Massive hadron pair production by 800 GeV/c protons on nuclear targets

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(Received 23 November 1992)

We report data on proton-nucleon collisions obtained on Fermilab experiment E711, in which high transverse momentum hadrons are produced near 90° in the proton-nucleon center of mass forming high mass states, using an 800 GeV/c proton beam on targets of beryllium, aluminum, iron, and tungsten. The data presented cover the mass range from 7 to 15 GeV/c^2, the three dihadron charge states $++$, $+-$, and $--$, and parton-parton scattering angles up to $\cos\theta^*=0.50$. We present the differential mass dihadron cross section, as well as the angular and charge dependence of the measurement. The cross section as a function of the parton-parton scattering angle for the three charge states is shown to vary linearly with the value of the atomic weight. While the angular distributions are shown to be independent of the target type, a small dependence on the charge state of the distributions is observed. The data are shown to be in good agreement with extrapolations from previous measurements and phenomenological QCD calculations.

PACS number(s): 13.85.Ni, 12.38.Qk, 25.40.Ve

I. INTRODUCTION

High transverse momentum hadronic production has been used to study QCD [1] since its discovery in 1972 [2]. The interpretation of data on the production of a single high p_T particle is complicated, however, by effects due to the intrinsic motion of the partons. Data from nuclear targets [3] may be further complicated both by collective nuclear effects on the intrinsic motion of the partons [4] and by interactions of the scattered partons with the nuclear matter. While data on leptonic hadron production from nuclear targets [5] suggest that for leading particles the latter effect is small, experiments using jetlike triggers [6] have found large nuclear effects. However, two particle inclusive reactions, with the two observed secondaries forming a high mass state ($M_{\text{pair}}\approx p_{T1}+p_{T2}$), can return the interpretation of the data to a simpler form. In particular, the calculated cross sections are insensitive to the initial state motions incorporated in models [7]. The present experiment was designed tc vestigate the hard scattering predictions of QCD in dronic collisions by observing such high mass dihac events in proton-nucleus collisions. We present data en between November 1987 and February 1988, on dependence of the cross section with atomic weight for the production of pairs of charged hadrons on nuclear targets, the dihadron mass cross sections, anc c.m. angular and charge dependence of the reac $p+\text{nucleus}\rightarrow H^{\pm}H^{\pm}+X$, measured by the Fermilat periment E711.

II. EXPERIMENTAL APPARATUS

The experiment was designed to observe high ı charged dihadron pairs over a large center-of-mass angle in the charge states $+-$, $++$, and $--$. Th paratus is shown in Fig. 1 and has been described iı tail in [8]. It was a double arm magnetic spectron with a calorimetric trigger. The two arms of the trac system were defined by deactivating central horiz bands of large aperture mini-drift-chambers to allov noninteracting beam and forward jets to pass thr unobserved. The two calorimeters were segmented cally to allow localized energy depositions to be us estimate the transverse momentum of particles ir trigger. Each calorimeter was supplemented with vertically segmented hodoscopes to identify the inc particles as charged. The 16 segments of each hodo and calorimeter formed a projective geometry to th get.

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3.9 E772 - THE QUARK-ANTIQUARK SEA IN NUCLEI

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E-772 made a precision measurement of the ratio of the yield of muon pairs from heavy nuclei to that from deuterium. This ratio of dimuon pairs (with masses from 6-9 GeV and 11-15 GeV, called Drell-Yan dimuons), is directly proportional to the distribution of anti-quarks in the proton and hence is sensitive to possible modifications of the sea of anti-quarks due to the nuclear environment. The experiment also studied the nuclear dependence of the yield of dimuons from the decay of J/ψ and ψ' resonances.

E772 Degree Recipients

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Ming-jer Wang	Ph.D.	Case Western Reserve University

E-772 Publications

Nuclear Dependence of Dimuon Production at 800 GeV/c., D.M. Alde, *et al.*, Phys. Rev. Lett. **64**, 2479 (1990).
A-Dependence of J/ψ and ψ' Production at 800 GeV/c., D.M. Alde, *et al.*, Phys. Rev. Lett. **66**, 133 (1991).
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Limit on the $\bar{d}$ / $\bar{u}$ Asymmetry of the Nucleon Sea from Drell-Yan Production., P.L. McGaughey, *et al.*, Phys. Rev. Lett. **69**, 1726 (1992).
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Nuclear Dependence of Dimuon Production at 800 GeV

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(Received 1 March 1990)

A precise measurement of the atomic-mass dependence of dimuon production induced by 800-GeV protons is reported. Over 450000 muon pairs with dimuon mass $M \geq 4$ GeV were recorded from targets of ^{2}H, C, Ca, Fe, and W. The ratio of dimuon yield per nucleon for nuclei versus ^{2}H, $R = Y_A/Y_{^2\mathrm{H}}$, is sensitive to modifications of the antiquark sea in nuclei. No nuclear dependence of this ratio is observed over the range of target-quark momentum fraction $0.1 < x_t < 0.3$. For $x_t < 0.1$ the ratio is slightly less than unity for the heavy nuclei. These results are compared with predictions of models of the European Muon Collaboration effect.

PACS numbers: 13.85.Qk, 25.40.Ve

The European Muon Collaboration (EMC) observed a modification of the quark structure of nucleons bound in heavy nuclei by studying the deep-inelastic scattering (DIS) of leptons.[1] The original EMC effect has been confirmed[2,3] in the region of fractional quark momenta $0.3 < x < 0.6$. The region $x \leq 0.1$, however, remains a subject of active experimental[4,5] and theoretical[6] activity.

After many years of intense effort, there is no consensus on the origin of the EMC effect. Continuum dimuon production in high-energy hadron collisions, known as the Drell-Yan[7] (DY) process, provides an independent measure of the modification of the quark structure of nuclei.[8] Proton-induced DY production, for fractional longitudinal momentum (Feynman x), $x_F \geq 0.2$, is dominated by the quark-antiquark annihilation subprocess

$$q_p + \bar{q}_t \to l^+ l^- ,$$

where p and t indicate the beam proton and target nucleon, respectively. Although there are large QCD corrections to the simple DY electromagnetic vertex, the factorization property of the next-to-leading-order QCD calculation ensures a DY dimuon yield proportional to the antiquark content of the target nucleon.[9] Thus proton-induced DY production is complementary to DIS where both quarks and antiquarks contribute.

Previous studies of the A dependence of the DY process performed at Fermilab and CERN[10,11] lack the statistical precision of the nuclear DIS data. In this paper we report the results of Fermilab experiment 772, a 450000-event measurement of DY dimuon production from nuclei in a kinematic regime that is sensitive to the antiquark distribution in the target nuclei.

Experiment 772 used a modified version of the large spectrometer in the Meson East beam line at Fermilab which was originally constructed for experiment 605.[12] The magnetic fields of the three dipole magnets of the spectrometer were configured to optimize acceptance for three different regions of dimuon mass. The spectrometer was used in a closed-aperture configuration. A thick hadron absorber in front of the first active detector per-

STRUCTURE OF PROTONS, NEUTRONS, AND MESONS
SECTION 4

Table of Contents

4. STRUCTURE OF PROTONS, NEUTRONS, AND MESONS

4.1 INTRODUCTION

There are some ways in which finding out what's inside a proton or neutron is analogous to finding out what's inside the nucleus of an atom: fire probing particles (say, electrons) of known energy at the nucleus, and look at the energy and angle of the scattered particles - a standard sort of "fluoroscopy by bombardment" technique. The electromagnetic interaction between the charge of the probe and the charge distribution of the nucleus will reveal how the target charges are arranged. If the probe energy is high enough, the target will disintegrate, and the fragments, their energies, and their angles, can be analyzed for clues to the composition and structure of the target.

In many ways, however, the story isn't quite so simple when it comes to nucleons and mesons. As the distance scale being probed decreases (with increasing probe energy), the fluoroscopy "evolves" in a way different from that of the atomic nucleus.

When a nucleon is probed at the greatest distance scale, it responds as a single object. At shorter lengths (higher probe energies), the momentum distribution of the three valence quarks is revealed and some of the momentum of the nucleon is observed to reside in the quanta of the color force, the gluons. At the smallest distance scales (highest probe energies), still more momentum carriers manifest themselves – a sea of quark-antiquark pairs coupled directly to the gluons. The momentum distributions of these constituent particles (valence quarks, sea quarks and antiquarks, and gluons, collectively called partons) are called the parton distribution functions. They are derived from the interaction probability (the cross-section) of the probe lepton as a function of energy and angle.

The parton distribution functions parameterize the input hadron structure distributions in the strong interaction description of lepton-hadron and hadron-hadron interactions. As such, they may also be investigated by studying the dynamics of many processes; e.g., single hard-photon production at high transverse momentum, the production of high-mass pairs of muons, and the production of heavy quarks. To the extent that these other processes are described by the same distribution functions, QCD is providing a reliable description of strong interactions. These other processes can then also be incorporated in the global fits to produce a better determined set of distribution functions. While most of the relevant measurements appear in experiments in this chapter, others can be found in Sections 3 and 5.

The universality of the parton distribution functions provides evidence for the reality of partons, objects which have never been observed in isolation (QCD predicts that this can never happen). The parton distribution functions form the backbone of our understanding of partons, and provide the basis for the predictive power of the Standard Model (and the base for searches for new phenomena that lie outside the Standard Model).

4.2 E605 - LEPTONS AND HADRONS NEAR THE KINEMATIC LIMITS

CERN (Switzerland), Columbia, Fermilab, KEK (Japan), Kyoto (Japan), Saclay (France), SUNY/Stony Brook, Washington

This experiment was designed to measure energetic electrons, muons, pions, kaons, and protons produced at large angles in the collision of 800 GeV protons with protons and neutrons in nuclei. The production of particles at large angles probes the quark, antiquark, and gluon structure of the proton and neutron much as the original Rutherfoord scattering experiment probed the structure of the atom.

E605 measured the production of massive muon pairs produced by the Drell-Yan mechanism - the annihilation of a quark and antiquark into a virtual photon which then decays to a muon pair. The measured muon pair yields from E605 are one of the important experimental inputs to perturbative QCD fits that yield the detailed momentum distribution of the quarks, antiquarks and gluons in the proton. E605 also measured the yield of pions, kaons and protons at large angles from nuclear targets with the aid of the large angular acceptance ring-imaging cerenkov counter (RICH). The ratios of the yields of these particles become constant at high transverse momenta, independent of momentum and target Z, as is expected in a QCD-parton description of particle production.

E605 Degree Recipients

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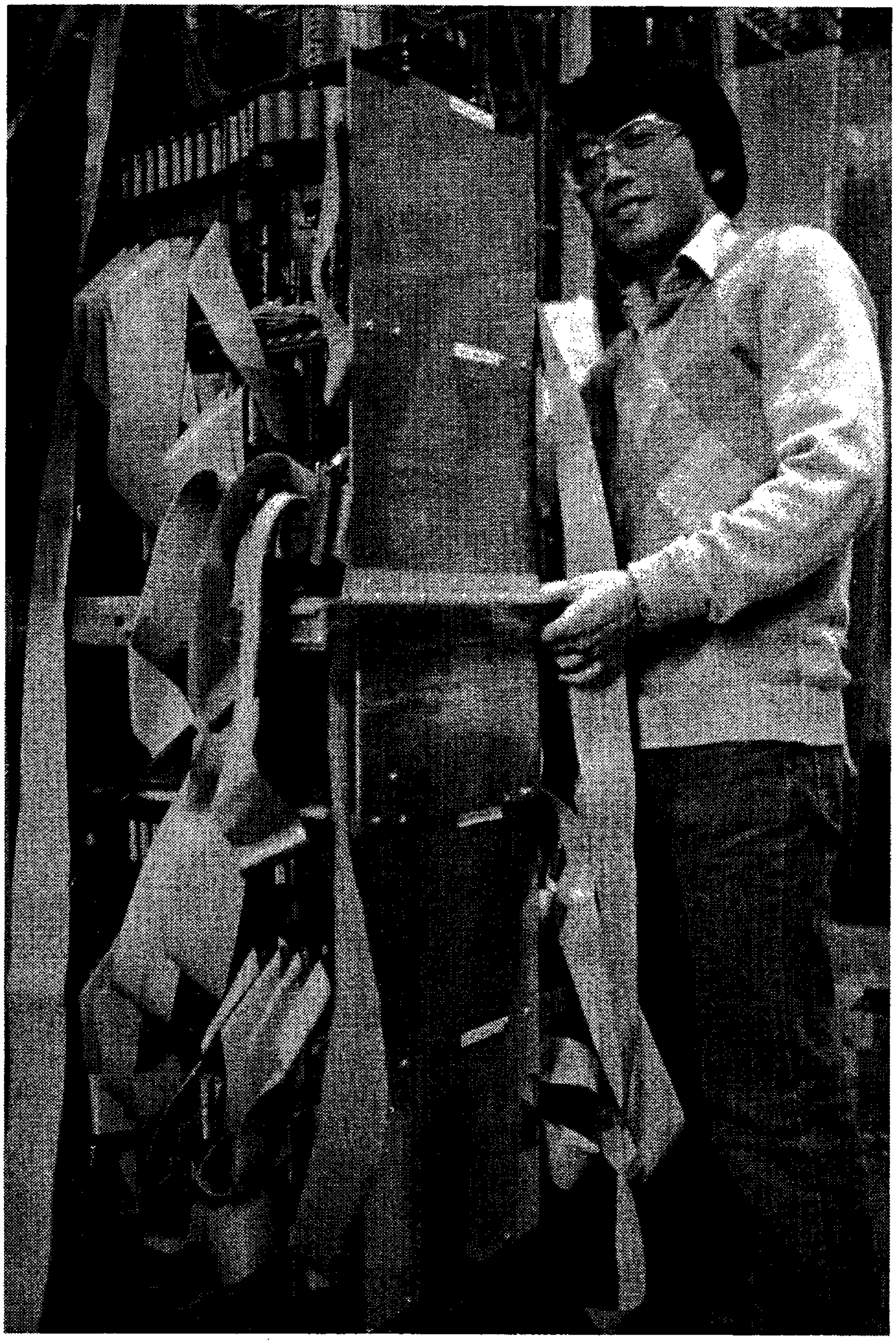

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Dimuon Production in 800-GeV Proton-Nucleus Collisions

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A measurement of continuum dimuon production in proton-copper collisions at 800-GeV incident energy is presented. The dimuons observed in this experiment cover the mass range from 6.5 to 18 GeV near $y=0$ in the proton-nucleon center-of-momentum frame. Scaling forms of the cross section for the continuum are compared with the results of other experiments in the context of the parton model and quantum chromodynamics. The present limitations of such scaling comparisons are discussed.

PACS numbers: 13.85.Qk, 12.38.Qk, 25.40.Ve

The study of lepton pairs produced in hadronic collisions,

$$h_A+h_B \to l^+l^-+X,$$

is sensitive to the structure of hadrons in a way complementary to inelastic lepton-nucleon scattering, $l+N \to l'+X$. After the first such experiment showed a steeply falling dimuon mass spectrum,[1] Drell and Yan[2] suggested that the underlying process might be production of a lepton pair by the electromagnetic annihilation of a parton-antiparton pair. Much experimental and theoretical work has confirmed many of the details of this description.[3] The advent of high-energy dimuon-yield measurements, combined with the derivation of order-α_s perturbative QCD corrections[4] to the lowest-order Drell-Yan mechanism, imposes significant constraints on hadron structure functions.

The E605 spectrometer[5] at Fermilab was used to perform a precise measurement of the 6–18-GeV mass spectrum of dimuons produced in 800-GeV proton-copper collisions. A 1.2-m-thick lead absorber, blocking the exit aperture of the 15-m spectrometer magnet, absorbed low-energy backgrounds. This allowed incident intensities of 2×10^{11} protons per second. The combination of a small target and a proportional-drift-tube chamber immediately following the absorber yielded an excellent mass resolution (σ_m/m) of 0.3% at 10 GeV.

The incident beam intensity was measured with a secondary-emission monitor (SEM) located approximately 100 m upstream of the target. This monitor was calibrated by measuring ^{24}Na activation in a copper foil temporarily placed in the beam. The data reported here correspond to 1.3×10^{17} incident protons and a total luminosity of 1.4×10^{42} cm^{-2} per nucleon, recorded using two different (but overlapping) mass settings of the spectrometer magnets.

The acceptance of the spectrometer was evaluated using a Monte Carlo simulation of the apparatus and the functional form for the cross section indicated in Table I. *This functional form was iterated until agreement* was reached with the observed distributions versus dimuon mass m and transverse momentum p_t. The assumed form versus dimuon x_F (taken from Rutherfoord[3]) has negligible effect on our results since we present cross sections differential in dimuon x_F or c.m. rapidity y, and the distribution versus Collins-Soper[6] angle θ_{CS} has been established by previous experiments.[3] The simulation included radiative corrections,[7] multiple-scattering and energy-loss effects in the lead absorber, and an accurate geometrical survey of the apparatus.

Results are presented as functions of the dimuon kinematic variables m or $\sqrt{\tau}=m/\sqrt{s}$ and x_F or y. An integration over the limited p_t of the dimuon was performed. Integrations over the angular variables were

4.3 E615 - FORWARD PRODUCTION OF MUON PAIRS

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This experiment studied the quark structure of the π meson, using the Drell-Yan process of $\mu^+\mu^-$ pair creation via a virtual photon in π-nucleus collisions. The data from E615 demonstrated that the momentum distribution of the valence quarks inside the pion extends to much larger fraction x of the pion's total momentum than is the case for quarks inside a proton or neutron. Also, it revealed a pattern of scaling violation in the quark distributions of the pion that is predicted by higher order scattering diagrams in QCD, known as a "higher twist effect".

E615 Degree Recipients

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E615 Publications

Measurement of the ratio of sea to valence quarks in the nucleon., J.G. Heinrich, *et al.*, Phys. Rev. Lett. **63**, 356 (1989).
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Measurement of the Ratio of Sea to Valence Quarks in the Nucleon

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The ratio of sea to valence quarks for nucleons in tungsten has been measured for the fractional momentum range $0.04 < x_N < 0.36$. The determination is based on the relative production rate of muon pairs by π^+ and π^- beams on a tungsten target. The results provide the most accurate determination to date of this ratio in the region $x_N < 0.1$ and $Q^2 > 20$ GeV^2, and are in good agreement with earlier measurements.

PACS numbers: 13.85.Qk, 14.20.Dh, 25.80.Ls

Lepton pair production by π^+ and π^- beams on a nuclear target affords a direct measurement of the ratio of sea to valence quarks in the nucleon. The method stems from the interpretation that lepton pair production at high energies proceeds through quark-antiquark annihilation.[1] In a kinematic regime where only valence quarks contribute and with a pure isoscalar target, the production ratio is $\frac{1}{4}$ (the square of the relative antiquark charge in the π^+ and π^- beams). In a regime where sea quarks from the nucleon also contribute, the ratio departs from $\frac{1}{4}$ because of the antiquarks in the nucleon sea. It is this difference from $\frac{1}{4}$ which provides a measurement of the nucleon sea-to-valence ratio and the ratio can be studied as a function of x_N, the fraction of the nucleon momentum carried by the annihilating quark.

The data for this measurement were obtained at Fermilab using π^+ and π^- beams at a momentum of 250 GeV/c incident on a tungsten target. Both beams were derived from 800-GeV/c protons. The negative-beam intensity was 4×10^9 per 20-s spill while the positive intensity was $(6-7)\times10^9$. The positive beam contained a proton contamination of 46% but, as shown below, this fraction can be determined from the data and leads to only a small correction.

The apparatus is shown in Fig. 1 and is described in detail in Ref. 2. It was built around two large dipole magnets. Hadrons produced in the tungsten target just upstream of the first magnet (p_T kick$=$3.2 GeV/c) were attenuated by a beryllium and a carbon absorber located in the magnet gap. High-mass muon pairs focused by this system traversed an analyzing spectrometer (p_T kick$=$0.86 GeV/c) located downstream. The spectrometer contained 25 planes of proportional or drift chambers for particle tracking and 8 scintillator planes for triggering. The trigger selected muon pairs with an estimated mass above 2.0 GeV/c^2. In changing from a negative to a positive pion beam, the currents in the two magnets were reversed but the setup was the same in all other respects. The apparatus was designed to have a large acceptance for muon pairs with a high longitudinal-

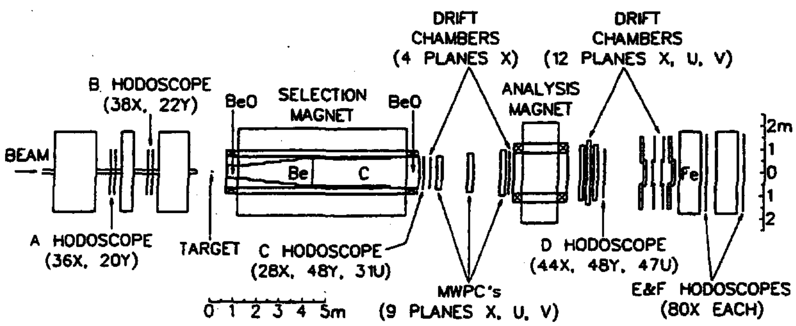

FIG. 1. Layout of the E615 apparatus.

4.4 E665 - MUON SCATTERING WITH HADRON DETECTION

ANL, UC/San Diego, Fermilab, Freiburg (Germany), Harvard, Illinois/Chicago, INP/Krakow (Poland), LLNL, Maryland, MIT, Max-Planck (Germany), Northwestern, Ohio, Pennsylvania, Washington, Wuppertal (Germany), Yale

Experiment E665 studied proton and nuclear structure using a high energy muon beam. Protons and neutrons are composed of partons; about half the momentum of a proton is carried by charged spin-1/2 quarks and the rest by neutral spin-1 gluons. Protons contain 3 valence quarks, which determine the quantum numbers of the proton, such as charge. However, in high energy experiments, protons also are observed to contain large numbers of force carriers (the gluons) and quark-antiquark pairs. The fraction of the proton or neutron momentum carried by a given quark can be measured by the recoil of a muon that interacts with that quark. The fraction is denoted by 'x'. The exact distribution of parton x between the valence quarks and the remaining quark antiquark pairs and gluons cannot yet be predicted from first principles, but the way in which such distributions change as the resolution of the probe (the inverse momentum transfer – 1/Q) varies, can be predicted by the theory of strong interactions Quantum Chromodynamics (QCD). The resolution dependence of proton structure scales with the logarithm of the momentum transferred by the probe, while the total rate for scattering can vary as a large power of the momentum transfer. As a result, precision measurements of large data samples are needed to disentangle the subtle logarithmic QCD effects from larger kinematic variations.

The E665 experiment was a continuation of both E98, an earlier Fermilab muon scattering experiment, which pioneered most of the techniques used in E665, and the EMC experiments at CERN. The Tevatron offered much higher beam energies and an improved beam with minimal halo. The E665 detector consisted of interchangeable hydrogen, deuterium, carbon, calcium, xenon and lead targets, high precision tracking chambers, electromagnetic calorimetry, and a final muon detector. The spectrometer had two magnets, one from the EMC experiment and one from E98. During the 1987 run, the vertex detector was a photographic streamer chamber from CERN experiment NA9, that yielded crucial information on the target fragmentation region for a subsample of the data.

Muon scattered in a range of angles as low as 1 mr, were detected and reconstructed. The high accuracy and large angular acceptance of the detector led to both absolute measurements of the proton and deuteron structure functions, and to precise measurements of the modifications of the parton distributions of nucleons bound in nuclei. These measurements covered the gap between the previous fixed target experiments and the HERA experiments H1 and Zeus, allowing determin-ation of the proton structure over a very large range of x and Q^2 values. Because E665 had wide solid angle coverage, other aspects of the interaction were also studied, notably the relations between 'shadowing' (the decrease of low momentum parton probabilities in heavy nuclei) and the presence or absence of diffractive interactions.

E665 Degree Recipients

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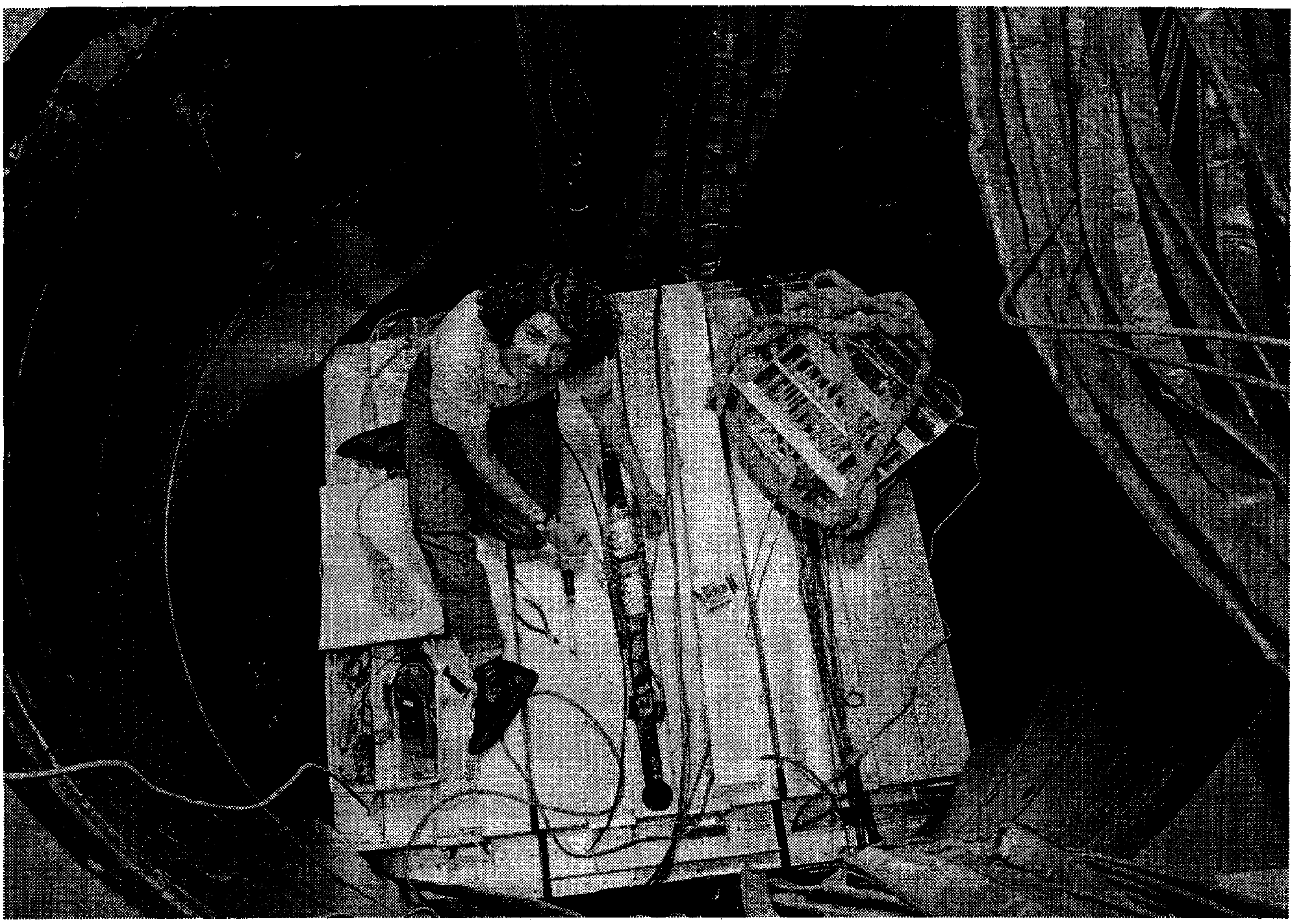

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Extraction of the Ratio F_2^n/F_2^p from Muon-Deuteron and Muon-Proton Scattering at Small x and Q^2

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The ratio of the deuteron to proton structure functions is measured at very small Bjorken x (down to 10^{-6}) and for $Q^2 > 0.001$ GeV^2 from scattering of 470 GeV muons on liquid hydrogen and deuterium targets. The ratio F_2^n/F_2^p extracted from these measurements is found to be constant, at a value of $0.935 \pm 0.008 \pm 0.034$, for $x < 0.01$. This result suggests the presence of nuclear shadowing effects in the deuteron. The dependence of the ratio on Q^2 is also examined; no significant variation is found.

PACS numbers: 13.60.Hb, 12.40.Vv, 24.85.+p, 25.30.Mr

In the large Q^2 region ($Q^2 > 1$ GeV^2), the parton model relates the small-x behavior of the structure function ratio of neutrons to protons (F_2^n/F_2^p) in muon-nucleon scattering to the light-flavor sea-quark composition of the nucleon. Here $x = Q^2/2M\nu$ is the Bjorken scaling variable, $-Q^2$ is the four-momentum transfer to the target nucleon squared, ν is the energy loss of the lepton in the laboratory frame, and M is the mass of the proton. From a different viewpoint, regardless of the magnitude of Q^2, the small-x limit of muon-nucleon scattering coincides with the Regge limit for this process, and in this limit the ratio is expected to approach unity [1]. The most recent experimental test of the Gottfried sum rule [2] used a measurement of F_2^n/F_2^p and a fit to existing data for F_2^d, the deuteron structure function, with a result that indicated a flavor asymmetry (i.e., $\bar{u} \neq \bar{d}$) of the light sea quarks [3]. The data cover $0.004 < x < 0.8$ and a Regge-inspired extrapolation is made to lower values of x. However, nuclear shadowing may be present at low x [4].

In this Letter, we present a measurement of the structure-function ratio F_2^n/F_2^p in muon-nucleon scattering on hydrogen and deuterium targets [5]. The data cover the kinematic range $10^{-6} \leq x \leq 0.3$ and 10^{-3} GeV$^2 \leq Q^2$. The only previous data below $x = 0.004$ are from an

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4.5 E733 - HIGH ENERGY NEUTRINO INTERACTIONS WITH THE TEVATRON QUADRUPOLE TRIPLET BEAM

Fermilab, Florida, MIT, Michigan State

This experiment was designed as a follow-on to E-594 and to act as a "first look" at high energy neutrino collisions from the first wide band beams at the Tevatron. The detector for this experiment was the 300 ton Flash-Chamber Proportional-Tube Calorimeter in Lab C constructed by the Fermilab, MIT, Michigan State Collaboration. The primary feature of this detector was the fine-grain sampling that allowed for the measurement of the direction of hadron showers. Shower energy at the Tevatron was determined by measuring the pulse height in the proportional tubes, and muon momenta were determined by large drift planes that were in the 12 ft. and 24 ft. toroidal magnets downstream of the calorimeter.

The original physics interest in this new regime (beyond the establishment of well-known behavior such as scaling), involved a variety of reactions which were hinted at in lower energy experiments as well as searching for new phenomena. The primary measurements involved determination of opposite sign dimuon final states, limits on weakly interacting massive particles, and detailed shower shapes.

E733 Degree Recipients

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E733 Publications

Study of Opposite-sign Dimuon Production in High Energy Neutrino Nucleon Interactions., B. Strongin, *et al.*, Phys. Rev. **D43**, 2778 (1991).
A Search for Weakly Interacting Massive Particles (WIMPS) in the Tevatron Wide Band Neutrino Beam., S. Gallas, *et al.*, Phys. Rev. **D52**, 6 (1995).

PHYSICAL REVIEW D VOLUME 43, NUMBER 9 1 MAY 1991

Study of opposite-sign dimuon production in high-energy neutrino-nucleon interactions

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Results are presented of a study of opposite-sign dimuon events observed in a fine-grained neutrino detector exposed to the Fermilab Tevatron wide-band neutrino beam. A total of 300 background-corrected $\mu^+\mu^-$ events induced by incident neutrinos and antineutrinos with energies up to 500 GeV were accumulated. The data were analyzed in terms of a model based on charm-quark production followed by semileptonic decay of the charmed meson. The Cabibbo-Kobayashi-Maskawa matrix terms were found to be $|U_{cd}|^2=0.0378\pm0.0127$ (stat)$^{+0.0099}_{-0.0082}$ (syst), and $\kappa|U_{cs}|^2=0.391\pm0.076$ (stat)$^{+0.097}_{-0.066}$ (syst). The ratio of the strange to nonstrange sea in the nucleon, $\kappa=2S/(\bar{U}+\bar{D})$; was measured to be 0.407 ± 0.075 (stat)$^{+0.103}_{-0.069}$ (syst).

I. INTRODUCTION

An attractive feature of opposite-sign dimuon production in neutrino-nucleon scattering is that it provides a window to the sea of nonvalence quarks in the nucleon. In particular, the data allow the abundance of strange quarks relative to nonstrange quarks to be determined. According to our present understanding, this abundance is controlled by Q^2-dependent QCD effects. Another benefit of a measurement of dimuons is that it permits a determination of the charged-current coupling strength of the charm quark with the down and the strange quarks. Given the new high-energy region opened up by the Fermilab Tevatron wideband neutrino beam, it was worthwhile to reexamine this process in a new high-energy region where there was the possibility that some new phenomenon may be uncovered.

The data of this study were obtained using a 340 metric ton fine-grained calorimeter[1] exposed to the quadrupole triplet wideband neutrino beam (QTB) at Fermilab. The pattern-recognition capabilities of the detector were useful in extracting the small dimuon signal and in studying its kinematic properties. The QTB offered a unique opportunity to study opposite-sign dimuon production at the highest available accelerator energies. Events were recorded with neutrino energies up to about 500 GeV.

After a brief discussion in Sec. II of the standard model of opposite-sign dimuon production, the details of the apparatus, event selection, background correction, incident-neutrino-flux normalization, and Monte Carlo simulation are described in Sec. III. The results are given in Sec. IV. There, several fits of the data to the standard model are discussed and the systematic errors of the fits are estimated. A summary is given in Sec. V.

II. THEORY

In the standard model, opposite-sign dimuons are produced in neutrino-nucleon scattering through the charged-current interaction where a charm (c) quark is created from a down (d) or a strange (s) quark. The c quark forms a charmed particle (most frequently a D meson) which may decay semileptonically into a muon with a charge opposite that of the outgoing muon from the primary neutrino-nucleon vertex. The process is depicted schematically in Fig. 1.

The cross section for opposite-sign dimuon production for incident neutrinos for an isoscalar target is given by[2]

$$d^3\sigma^\nu/dx\,dy\,dz=(G_F^2ME_\nu/2\pi)\xi\{[u(\xi)+d(\xi)]|U_{cd}|^2 +2s(\xi)|U_{cs}|^2\} \times(1-m_c^2/2ME_\nu\xi)D(z)B_c\ , \quad (1)$$

where G_F is the Fermi constant; E_ν is the incident neutrino energy; M is the nucleon mass; U_{cd} and U_{cs} are Cabibbo-Kobayashi-Maskawa (CKM) matrix elements;[3] $u(\xi)$, $d(\xi)$, and $s(\xi)$ are the up-, down-, and strange-quark structure functions, respectively. The large effective mass of the charm quark m_c expected to be of

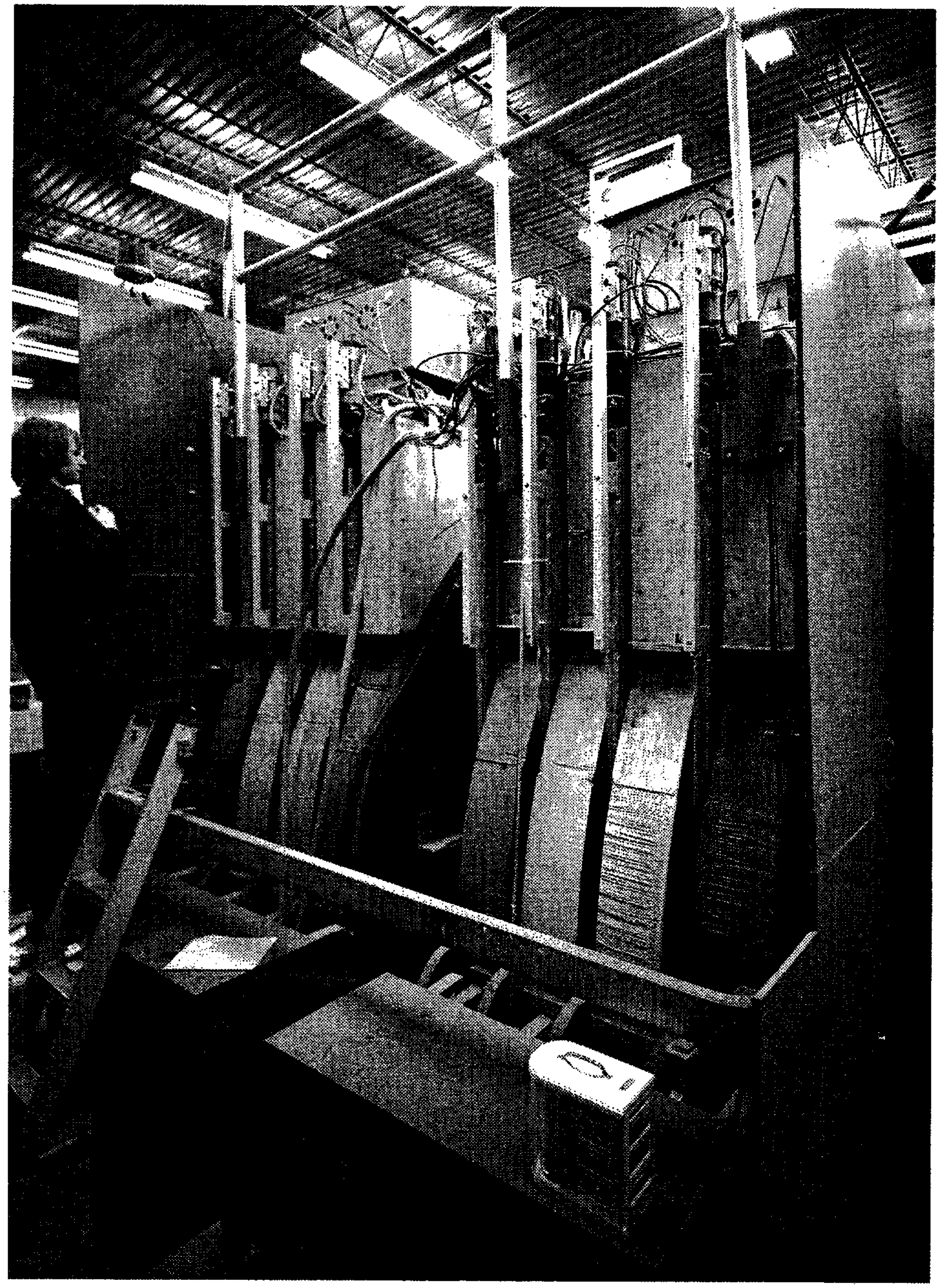
4.6 E744/770 - NEUTRINO PHYSICS AT THE TEVATRON

Chicago, Columbia, Fermilab, Rochester, Wisconsin

In 1983, a major threat to the Standard Model of particle physics was the observation of same-sign dimuons, two muons of the same sign, produced in neutrino interactions in unexpectedly large numbers and at a rate that rose with energy. The high-energy, high-intensity neutrino beam from the Tevatron provided physicists on E744 with the opportunity to examine this anomaly. While this investigation was a primary goal (and E744's analysis showed that the behavior of this process did in fact agree with the Standard Model), it was far from the experiment's only purpose.

E744 (which ran in 1985) and its immediate successor, E770 (1987-88), set forth to perform a high-statistics, high-energy measurement of the neutrino cross sections; to extract nucleon structure functions (fundamental distributions describing weak interactions on nuclear matter) and the distributions of quark momenta in nucleons; and to test the theory of the strong interaction, Quantum Chromodynamics (QCD), by looking at opposite-sign dimuons and measuring the strong interaction coupling constant. These measurements were accomplished by operating the wide-band neutrino beam, generated by targeting the Tevatron proton beam onto a block of beryllium oxide, and magnetically focusing the secondary charged particles through a long beam tube (aimed at the detector), where they decayed into an intense mixed beam of energetic neutrinos and antineutrinos. The physicists used the Lab E detector, an instrumented iron target calorimeter (to measure particle position and energy) followed by a magnetic spectrometer (to determine the momentum of penetrating muons). The calorimeter utilized sandwiched scintillation counters and drift chambers, between ten-foot-square, two-inch-thick plates of steel, to form a 690-ton detector nearly sixty feet in length.

By 1992, the Standard Model was in such good shape that precision measurements of its fundamental parameters (such as the weak mixing angle, which describes how the weak and electromagentic forces unite) could signal new physics. Improvements in collider experiments meant that the value of this mixing angle, measured first in neutrino scattering, could now be determined by means of several extremely different processes. Once again, neutrino scattering could put the Standard Model to a stringent test. However, achieving this improvement required the use of a new technique, employing separate neutrino and antineutrino beams. Measuring the weak mixing angle using these separate beams was a major goal of a future experiment, E815 described in Section 7.



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E744/E770 Publications

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VOLUME 79, NUMBER 7 PHYSICAL REVIEW LETTERS 18 AUGUST 1997

Improved Determination of α_s From Neutrino-Nucleon Scattering

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We present an improved determination of the proton structure functions F_2 and xF_3 from the Columbia-Chicago-Fermilab-Rochester Collaboration ν-Fe deep inelastic scattering experiment. Comparisons to corrected high-statistics charged-lepton scattering results for F_2 from the NMC, E665, SLAC, and BCDMS experiments indicate good agreement for $x > 0.1$ but some discrepancy at lower x. The Q^2 evolution of both the F_2 and xF_3 structure functions yields a value of the strong coupling constant at the scale of mass of the Z boson of $\alpha_s(M_Z^2) = 0.119 \pm 0.002(\text{expt}) \pm 0.004(\text{theory})$. This is one of the most precise measurements of this quantity. [S0031-9007(97)03809-X]

PACS numbers: 12.38.Qk, 13.15.+g, 24.85.+p, 25.30.Pt

High-energy neutrinos are a unique probe for testing quantum chromodynamics (QCD) and understanding the parton properties of nucleon structure. Combinations of neutrino and antineutrino scattering data are used to determine the F_2 and xF_3 structure functions (SFs) which determine the valence, sea, and gluon parton distributions in the nucleon [1,2]. The universalities of parton distributions can also be studied by comparing neutrino and charged-lepton scattering data. Past measurements have indicated that F_2^{ν} differs from $F_2^{e/\mu}$ by 10%–20% in the low-x region. These differences are larger than the quoted experimental errors of the measurements and may indicate the need for modifications of the theoretical modeling to include higher-order or new physics contributions. QCD predicts the scaling violations (Q^2 dependence) of F_2 and xF_3 and, experimentally, the observed scaling violations can be tested against those predictions to determine α_s [3] or the related QCD scale parameter, Λ_{QCD}. The α_s determination from neutrino scattering has a small theoretical uncertainty since the electroweak radiative corrections, scale uncertainties, and next-to-leading order (NLO) corrections are well understood.

In this paper, we present an updated analysis of the Columbia-Chicago-Fermilab-Rochester (CCFR) Collaboration neutrino scattering data with improved estimates of quark model parameters [4] and systematic uncertainties. The α_s measurement from this analysis is one of the most precise due to the high energy and statistics of the experiment compared to previous measurements [5].

The differential cross sections for the ν-N charged-current process $\nu_\mu(\overline{\nu}_\mu) + N \to \mu^-(\mu^+) + X$, in terms of the Lorentz-invariant structure functions F_2, $2xF_1$, and xF_3 are

$$\frac{d\sigma^{\nu,\overline{\nu}}}{dx\,dy} = \frac{G_F^2 M E_\nu}{\pi}\left[\left(1 - y - \frac{Mxy}{2E_\nu}\right)F_2(x,Q^2) + \frac{y^2}{2}2xF_1(x,Q^2) \pm y\left(1 - \frac{y}{2}\right)xF_3(x,Q^2)\right], \quad (1)$$

where G_F is the weak Fermi coupling constant, M is the nucleon mass, E_ν is the incident neutrino energy, Q^2 is the square of the four-momentum transfer to the nucleon, the scaling variable $y = E_{\text{had}}/E_\nu$ is the fractional energy transferred to the hadronic vertex with E_{had} equal to the measured hadronic energy, and $x = Q^2/2ME_\nu y$, the Bjorken scaling variable, is the fractional momentum carried by the struck quark. The structure function $2xF_1$ is expressed in terms of F_2 by $2xF_1(x,Q^2) = F_2(x,Q^2) \times \frac{1+4M^2x^2/Q^2}{1+R(x,Q^2)}$, where $R = \frac{\sigma_L}{\sigma_T}$ is the ratio of the cross section of longitudinally to transversely polarized W bosons. In the leading-order quark-parton model, F_2 is the singlet distribution $xq^S = x\sum(q + \overline{q})$, the sum of the momentum densities of all interacting quark constituents, and xF_3 is the nonsinglet distribution $xq^{NS} = x\sum(q - \overline{q}) = xu_V + xd_V$, the valence quark momentum density; these relations are modified by higher-order QCD corrections.

The neutrino deep inelastic scattering (DIS) data were taken in two high-energy high-statistics runs, FNAL E744 and E770, in the Fermilab Tevatron fixed-target quadrupole triplet beam (QTB) line by the CCFR

4.7 E745/782 - THE TOHOKU HIGH-RESOLUTION BUBBLE CHAMBER

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E-745 was a muon-neutrino experiment using the Tohoku high-resolution one-meter freon bubble chamber. High spatial resolution of 70 μm was obtained with holographic optics. The physics aims were: (1) studies of neutrino interactions in the high Q^2 region, (2) studies of charm and heavy quarks, and (3) new phenomena, e.g. tau neutrino events. During the 1985 and 1987 fixed target runs, 200,000 and 360,000 pictures were taken, respectively.

E-782 was a muon exposure in the Tohoku High-Resolution One-Meter Freon Bubble Chamber. Unique features of this experiment were the observation of vertices with high-resolution optics, and low Q^2 data with small systematic bias. The analysis included 8163 events above $E_\nu = 1$ GeV.

E-745 Degree Recipients

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E745 Publications

A New Method to Investigate the Nuclear Effect in Leptonic Interactions., T. Kitagaki, *et al.*, Phys. Lett. **B214**, 281 (1988).

E782 Degree Recipients

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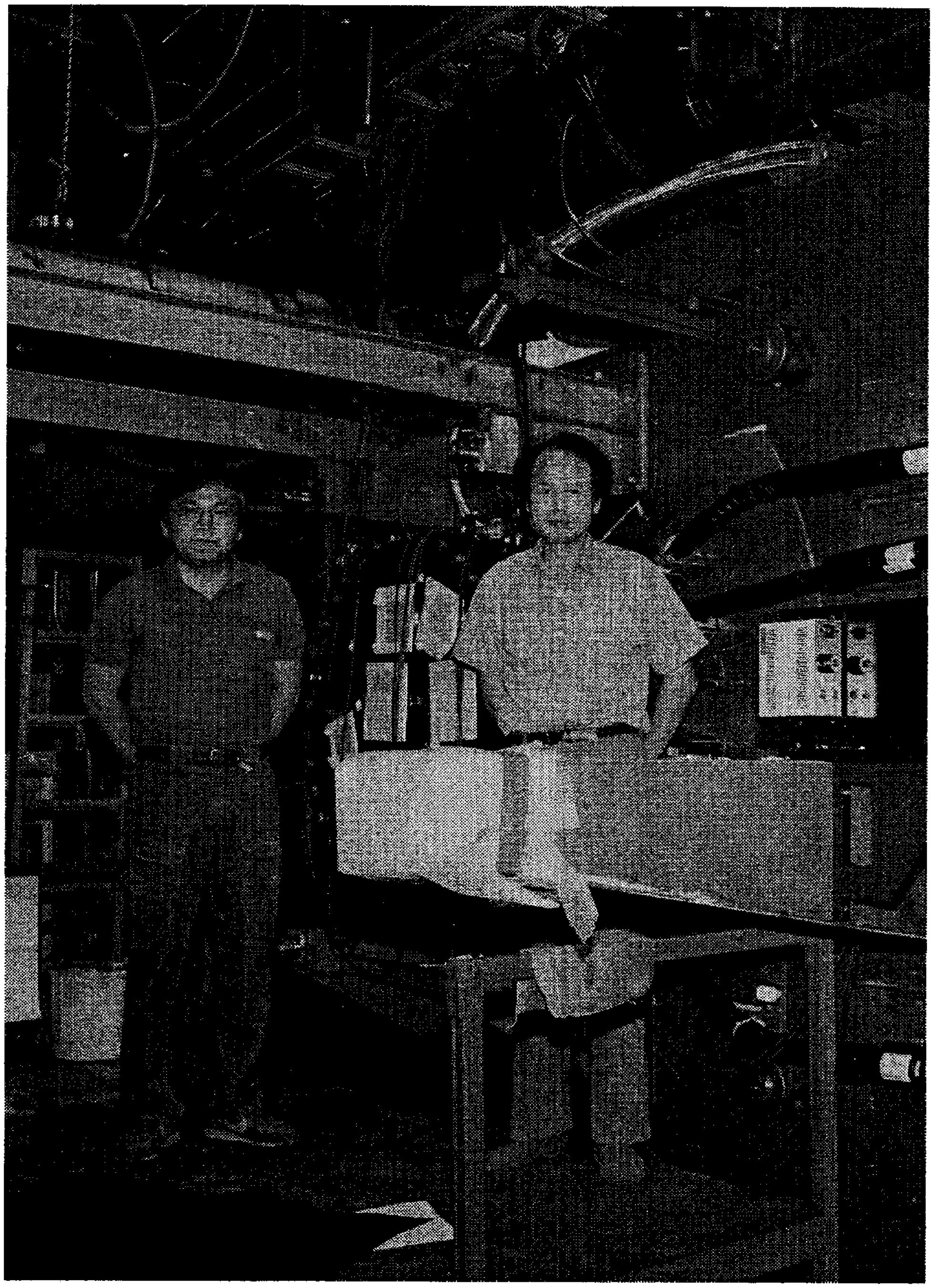

e 214, number 2 PHYSICS LETTERS B 17 November 1988

A NEW METHOD TO INVESTIGATE THE NUCLEAR EFFECT IN LEPTONIC INTERACTIONS

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High energy neutrino interactions in a heavy liquid bubble chamber were classified by the presence or absence of dark tracks (stubs) at the interaction vertices. Quark distributions, $\sigma(x)$, were compared in the two groups of data. Those with dark tracks, presumably indicative of an interaction with a deeply bound nucleon, show an enhanced nuclear effect.

4.8 E866 - MEASUREMENT OF ANTI-D(X)/ANTI-U(X) IN THE PROTON

Abilene Christian, ANL, Fermilab, Georgia State, IIT, LANL, Louisiana, New Mexico State, New Mexico, ORNL, Texas A&M, Valparaiso

E-866 (NuSea) made a precision measurement of the yield of oppositely charged pairs of muons (with masses between 6-9 GeV and 11-15 GeV, so called Drell-Yan dimuons) from protons incident on hydrogen and deuterium targets. According to the QCD description of muon pair production, the Drell-Yan dimuon yield is directly proportional to the antiquark composition of the nucleon. The E866 results greatly improve the experimental knowledge of the ratio of d-antiquark to u-antiquark in the proton versus, the fractional antiquark momentum, designated 'x'. The observed asymmetry of d-antiquark to u-antiquark has resulted in newer parameterizations of the distribution of quarks and antiquarks in the nucleon. Bound state non-perturbative effects, such as virtual meson formation, are thought to be the source of the observed asymmetries.

In addition, E866 made measurements of the Drell-Yan, J/ψ, ψ', and upsilon yields, and angular distributions from nuclear targets over broad ranges in x_F and p_T. The yield and polarization of these states can be compared with theoretical predictions.

E866 Degree Recipients

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R.S. Towell	Ph.D.	University of Texas at Austin
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E866 Publications

Measurement of the Light Antiquark Flavor Asymmetry in the Nucleon Sea., E.A. Hawker, *et al.*, Phys. Rev. Lett. **80**, 3715 (1998).
$\bar{d}/\bar{u}$ *Asymmetry and the Origin of the Nucleon Sea .*, J.C. Peng, *et al.*, Phys. Rev. **D58,** 92004 (1998).
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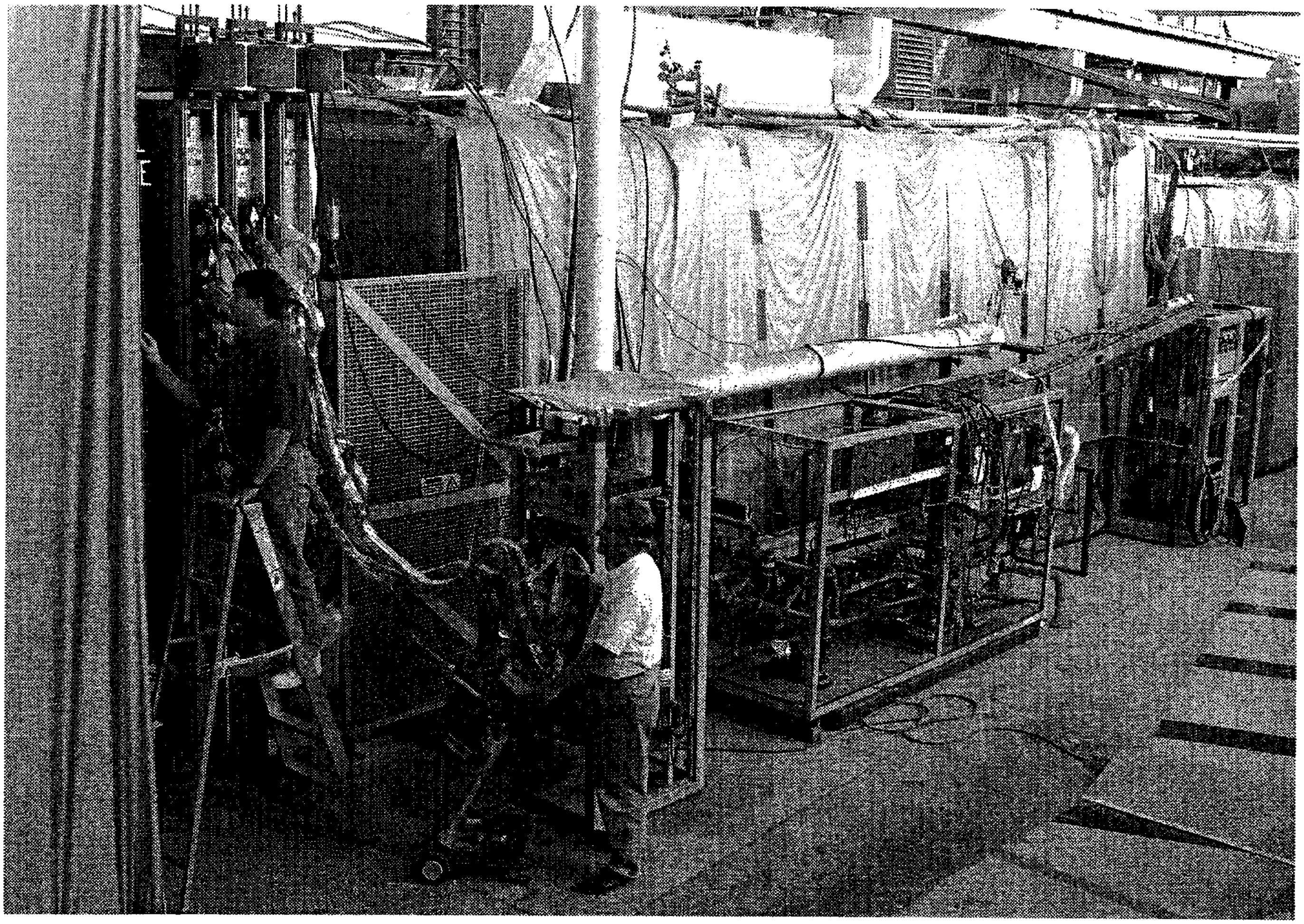

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Measurement of the Light Antiquark Flavor Asymmetry in the Nucleon Sea

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(Received 9 December 1997; revised manuscript received 13 February 1998)

A precise measurement of the ratio of Drell-Yan yields from an 800 GeV/c proton beam incident on hydrogen and deuterium targets is reported. Over 140 000 Drell-Yan muon pairs with dimuon mass $M_{\mu^+\mu^-} \geq 4.5$ GeV/c^2 were recorded. From these data, the ratio of antidown ($\bar{d}$) to antiup ($\bar{u}$) quark distributions in the proton sea is determined over a wide range in Bjorken x. A strong x dependence is observed in the ratio $\bar{d}/\bar{u}$, showing substantial enhancement of $\bar{d}$ with respect to $\bar{u}$ for $x < 0.2$. This result is in fair agreement with recent parton distribution parametrizations of the sea. For $x > 0.2$, the observed $\bar{d}/\bar{u}$ ratio is much nearer unity than given by the parametrizations. [S0031-9007(98)05905-5]

PACS numbers: 13.85.Qk, 14.20.Dh, 24.85.+p, 25.40.Ve

No known symmetry requires equality of the $\bar{d}$ and $\bar{u}$ distributions in the proton. Until recently it had been generally assumed that $\bar{d}(x) = \bar{u}(x)$ for lack of experimental evidence to the contrary. This assumption may be evaluated by use of the expression

$$\int_0^1 [F_2^p(x) - F_2^n(x)]\frac{dx}{x} = \frac{1}{3} - \frac{2}{3}\int_0^1 [\bar{d}_p(x) - \bar{u}_p(x)]\,dx\,. \quad (1)$$

Here $F_2^p(x)$ and $F_2^n(x)$ are the proton and neutron inelastic structure functions, and $\bar{d}_p(x)$ and $\bar{u}_p(x)$ are the antidown and antiup quark distributions in the proton sea as a function of Bjorken x. Equation (1) requires the assumption of charge symmetry between the proton and neutron (i.e., $u_p = d_n$, $\bar{u}_p = \bar{d}_n$, etc.). If the nucleon sea is flavor symmetric in the light quarks, the value of the integral on the left is 1/3, a result referred to as the Gottfried sum rule (GSR) [1]. In 1991 the New Muon Collaboration (NMC) at CERN presented evidence that the GSR is violated, based on deep inelastic muon scattering data from hydrogen (p) and deuterium (d). They reported a final value of $\int_0^1[F_2^p(x) - F_2^n(x)]\frac{dx}{x} = 0.235 \pm 0.026$ [2], which implies that

$$\int_0^1 [\bar{d}_p(x) - \bar{u}_p(x)]\,dx = 0.147 \pm 0.039\,, \quad (2)$$

a considerable excess of $\bar{d}_p$ relative to $\bar{u}_p$. This result has been adopted in the most current parametrizations of the parton distributions in the nucleon [3,4].

Following publication of the NMC result, the use of the Drell-Yan process [5] was suggested [6] as a means by which the light antiquark content of the proton could be more directly probed. This was first done by the Fermilab E772 Collaboration. They compared the production of Drell-Yan muon pairs from isoscalar targets to that from a neutron rich target. This measurement sets constraints on the nonequality of $\bar{u}$ and $\bar{d}$ in the range $0.04 \leq x \leq 0.27$ [7]. Later, the CERN experiment NA51 [8] carried out a comparison of the Drell-Yan muon pair yield from hydrogen and deuterium at a single value of x using a 450 GeV/c proton beam and found

$$\left.\frac{\bar{u}_p}{\bar{d}_p}\right|_{\langle x\rangle = 0.18} = 0.51 \pm 0.04 \pm 0.05\,. \quad (3)$$

A recent review by Kumano [9] presents an extensive discussion of the existing literature on the flavor asymmetry of the antiquark sea.

THE PHYSICS OF CHARM AND BEAUTY
SECTION 5

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5. PHYSICS OF CHARM AND BEAUTY

5.1 INTRODUCTION

Two of the fundamental particles of the standard model are the charm quark and the beauty quark, the latter sometimes known as the bottom quark. In spite of their quaint names, these quarks have both played, and continue to play critical roles in particle physics research. The charm quark was the real spark for the acceptance of the whole picture of the quark-lepton substructure of matter. The bottom quark is now the focus of extensive studies around the world, studies which aim at understanding the details of standard-model CP violation and of the matter-antimatter asymmetry observed in experiments. More hopefully, these studies may find a glimpse of what lies beyond the standard model. Fermilab fixed-target experiments on particles containing charm quarks have provided guideposts in the understanding of CP violation. Given that the standard model explanation for the CP violation seen in the laboratory cannot explain the mysterious asymmetry in the matter-antimatter balance in the universe, there must be something beyond the standard model. Charm and beauty studies may hold the key to this and other tantalizing questions in particle physics. The mixing of charm particle and antiparticle, and the searches for rare and forbidden decays may open unexpected doors. Also, we may hope that a detailed study of physics involving charm and bottom quarks, when combined with the study of the other quarks, will lead to an understanding of why nature has arranged the quarks into three generations, with each generation containing two sometimes quite different quarks.

Even in the area of standard-model physics, there are important questions to which fixed-target experiments at Fermilab have contributed answers: how quarks are produced in high-energy interactions, how those quarks turn into the particles seen in the laboratory, and the dynamics leading to the decay of particles containing charm quarks. For example, since the charm and bottom quarks are produced dominantly by the fusion of bits of the glue that binds quarks within the particles that are seen directly in the laboratory, charm quark production properties may be used to study the distribution of the glue in particles. Also, the decay of charm particles provides a particularly clean environment in which to study the characteristics of those particles into which the charm particles decay. The recent charm experiments are providing answers that have eluded physicists for decades. The copious decays observed in Fermilab fixed-target experiments provide a unique way of studying the low-mass resonances of pairs of pions and of pions and kaons. These measurements complement those made historically in scattering experiments at lower energies.

Major contributions from the charm and beauty fixed target program also have been in the areas of detector development, and data acquisition and computing. The rarity of charm and beauty quarks in fixed target interactions and the unique decay properties of these quarks led experimenters to implement silicon microstrip detectors, trigger processors, fiber readout of scintillating plastics, high speed data readout, and web-based monitoring. Creativity, trying non-standard techniques, and diverse and innovative beams have marked this fixed target program. Each experiment tried a different wrinkle to advance the science.

5.2 E400 - CHARMED PARTICLE PRODUCTION BY NEUTRONS

University of Bologna (Italy), University of Colorado, Fermi National Accelerator Laboratory, University of Illinois, INFN, Milano (Italy), University of Pavia (Italy), Yale University

E400 was designed to study the neutron production and properties of charm particles. E400 featured a novel, high resolution MWPC called the D5 to enable the experiment to tag charm particles through their very short, but finite lifetime. The D5 was a precursor to much finer pitched microstrip detectors which emerged in the next generation of charm experiments a few years later and revolutionized charm particle reconstruction in fixed target environments. E400 was able to confirm the first evidence for the existence of the Ξ_c^+ baryon, the first baryon observed that has both charm and strange quark content.

E400 also measured the Ξ_c^+ lifetime with greater precision than known previously. Another E400 highlight was the first observation of the neutral D meson decaying into a final state consisting of two K_s^o mesons. This is an especially interesting final state. It is not expected to occur directly because of an interesting cancellation of contributions. It is likely to be produced through final-state re-scattering in other, direct decays.

E400 Degree Recipients

F. Bossi	Ph.D.	University of Pavia
Janice Enagonio	Ph.D.	University of Colorado
John Eugene Filaseta	Ph.D.	University of Illinois at Urbana-Champaign
Thomas Knight Kroc	Ph.D.	University of Illinois at Urbana-Champaign
Raymond Ladbury	Ph.D.	University of Colorado
Calvin L. Shipbaugh	Ph.D.	University of Illinois at Urbana-Champaign

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Production of the $D_s^\pm$ *by high energy neutrons.*, C. Shipbaugh, *et. al.*, Phys. Rev. Lett. **60**, 2117 (1988).

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Production of the $D_s^\pm$ by High-Energy Neutrons

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(Received 11 December 1987)

We have observed the production of the $D_s^\pm$ by a high-energy neutron beam on nuclear targets. The $D_s^\pm$ was observed in the decay mode $D_s^\pm \to \phi\pi^\pm$, $\phi \to K^+K^-$. The average of the inclusive cross sections for D_s^+ and D_s^- hadroproduction is measured to be $B\,d\sigma/dx_F = 2.85 \pm 0.80 \pm 0.86$ μb/nucleon at $x_F = 0.175$ on the assumption of a linear A dependence, where $B \equiv \Gamma(D_s^\pm \to \phi\pi^\pm)/\Gamma(D_s^\pm \to \text{all})$.

PACS numbers: 13.85.Ni, 13.25.+m, 14.40.Jz

We have measured the cross section times branching fraction for hadroproduction of the decay mode $D_s^\pm \to \phi\pi^\pm$. This mode has been previously observed[1] in e^+e^- annihilation to have a mass of $1970 \pm 5 \pm 5$ MeV/c^2 and has since been confirmed by several observations. Several experiments have measured the branching fraction for $D_s^\pm \to \phi\pi^\pm$, but the value is not yet well determined.[1-4] Previously published information on the hadroproduction of the D_s^+ has been severely statistics limited.[5,6] We have observed a 64-event $D_s^\pm \to \phi\pi^\pm$ signal at a mass of 1972 ± 5 MeV/c^2 produced by high-energy neutrons.

The experiment was performed in the Proton East beam line at Fermi National Accelerator Laboratory. The incident neutron beam was formed by 800-GeV protons incident on a beryllium target. The neutron energy spectrum ranged from 0 to 800 GeV and was triangular in shape, with a most probable energy at 640 GeV ($\sqrt{s}$ of 35 GeV). The contribution to the neutral beam from photons and K_L^0's above 200 GeV was negligible.

A layout of the apparatus and detailed description of the spectrometer have been given previously.[7] Briefly, the detector consists of an active target and vertex detector, a magnetic spectrometer, a gas Cherenkov system, and electromagnetic and hadronic calorimetry. The target was composed of three segments consisting of tungsten, silicon, and beryllium. The total event energy was obtained by summation of the output of the electromagnetic, hadronic, and beam dump calorimetry. The summed response of the electromagnetic and hadronic calorimeters was used as our minimum-energy trigger.

Charged-particle identification was accomplished with use of three 34-cell Cherenkov counters, operating (from upstream to downstream) with pion thresholds of 2.8, 10.8, and 5.7 GeV/c, respectively. Protons could be uniquely identified from 10 to 80 GeV/c, while unique kaon identification extended from 10 to 40 GeV/c.

The data for this analysis consisted of approximately 45×10^6 events. The event trigger required that all of the following conditions be satisfied: (a) a coincidence between a target-region scintillation counter and two coincidences in a downstream scintillator hodoscope; (b) a minimum calorimeter trigger energy of 265 GeV; (c) a minimum multiplicity of four charged tracks in the downstream spectrometer; (d) a deposited charge in the most downstream active silicon target equivalent to two or more charged tracks; (e) at least one charged kaon with momentum over 21 GeV/c or one proton over 40 GeV/c traversing the entire detector. All triggers satisfying requirements (a) through (e) were subject to a procedure which found all charged tracks and a common vertex, and which then performed a Cherenkov-counter analysis.

Figure 1 shows a K^+K^- invariant-mass distribution with a prominent ϕ signal. Each kaon candidate is required to be uniquely Cherenkov identified (i.e., unambiguous with either the pion or proton hypothesis). Because this state has a natural width comparable to our spectrometer resolution, we have performed the fit to the signal by the convolution of a Breit-Wigner shape of appropriate width[8] with a Gaussian distribution. The background has been fitted by a third-order polynomial. The result is 33000 candidates with a mass at 1019.5 MeV/c^2. We selected ϕ candidates by applying a K^+K^- mass cut of 1019.5 ± 3.5 MeV/c^2.

To perform the $D_s^\pm$ search, these ϕ candidates were combined with charged tracks, with the assumption of a

5.3 E653 - CHARM AND BEAUTY DECAYS IN A HYBRID EMULSION SPECTROMETER

Aichi (Japan), UC/Davis, Carnegie-Mellon, Chonnam National (Korea), Fermilab, Gifu (Japan), Gyeongsang National (Korea), Joenbug (Korea), Kinki (Japan), Kobe (Japan), Korea (Korea), Nagoya (Japan), Nagoya Inst. of Tech. (Japan), Ohio State, Okayama (Japan), Oklahoma, Osaka City (Japan), Osaka Sci. Ed. Center. (Japan), Toho (Japan), Utsunomiya (Japan), Yokohama National (Japan), Won Kwang (Korea)

E653 studied short-lived charm and beauty particles produced by high-energy pion and proton beams. The experiment's unique feature incorporated a hybrid of emulsion target and conventional spectrometer. Decay candidate events to be scanned in the emulsion were selected and located with a silicon microstrip vertex detector. The emulsion target allowed the chosen events to be examined with sub-micron resolution. E653 had exceptionally good muon identification, and used a muon trigger to enrich the recorded sample of beauty events and of semimuonic and purely muonic decays of charm. The experiment used nine fully-reconstructed beauty quark-antiquark pairs to study production properties at fixed-target energies and to measure beauty lifetimes. It made an excellent measurement of semileptonic decay form factors for $D^+ \rightarrow$ *anti-*K^{*o}*(892)* $\mu\, \nu_\mu$, made the first observation of $D^+ \rightarrow \rho\, \mu\, \nu_\mu$, and the first form factor measurements for $D_s^+ \rightarrow \phi\, \mu\, \nu_\mu$. The experiment used its hybrid capabilities to full advantage to do physics otherwise inaccessible: good limits for flavor-changing neutral current decays of charm in multineutral modes, and for possible four- and five-body semileptonic decays of charm; and a study of $D_s^+ \rightarrow \mu\, \nu_\mu$. This very interesting purely leptonic decay is very difficult to study in conventional spectrometers because of its one-prong "kink" topology, but is ideally suited to E653's hybrid emulsion technique.

E653 Degree Recipients

T. Abe	Ph.D.	Kobe University
M. Adachi	M.S.	Toho University
James M. Dunlea	Ph.D.	Ohio State University
K. Ebara	M.E.	Utsunomiya University
Arne P. Freyberger	Ph.D.	Carnegie Melon University
K. Fujiwara	M.S.	Kobe University
O. Fukuda	M.E.	Utsunomiya University
K. Horie	M.E.	Utsunomiya University
S. Ikegami	M.S.	Toho University
N. Itou	M.S.	Kobe University
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M. Komatsu	Ph.D.	Nagoya University
T. Koya	M.S.	Toho University
Akbar Mokhtarani	Ph.D.	University of California at Davis
William R. Nichols	Ph.D.	Carnegie Melon University
E. Niu	M.S.	Toho University
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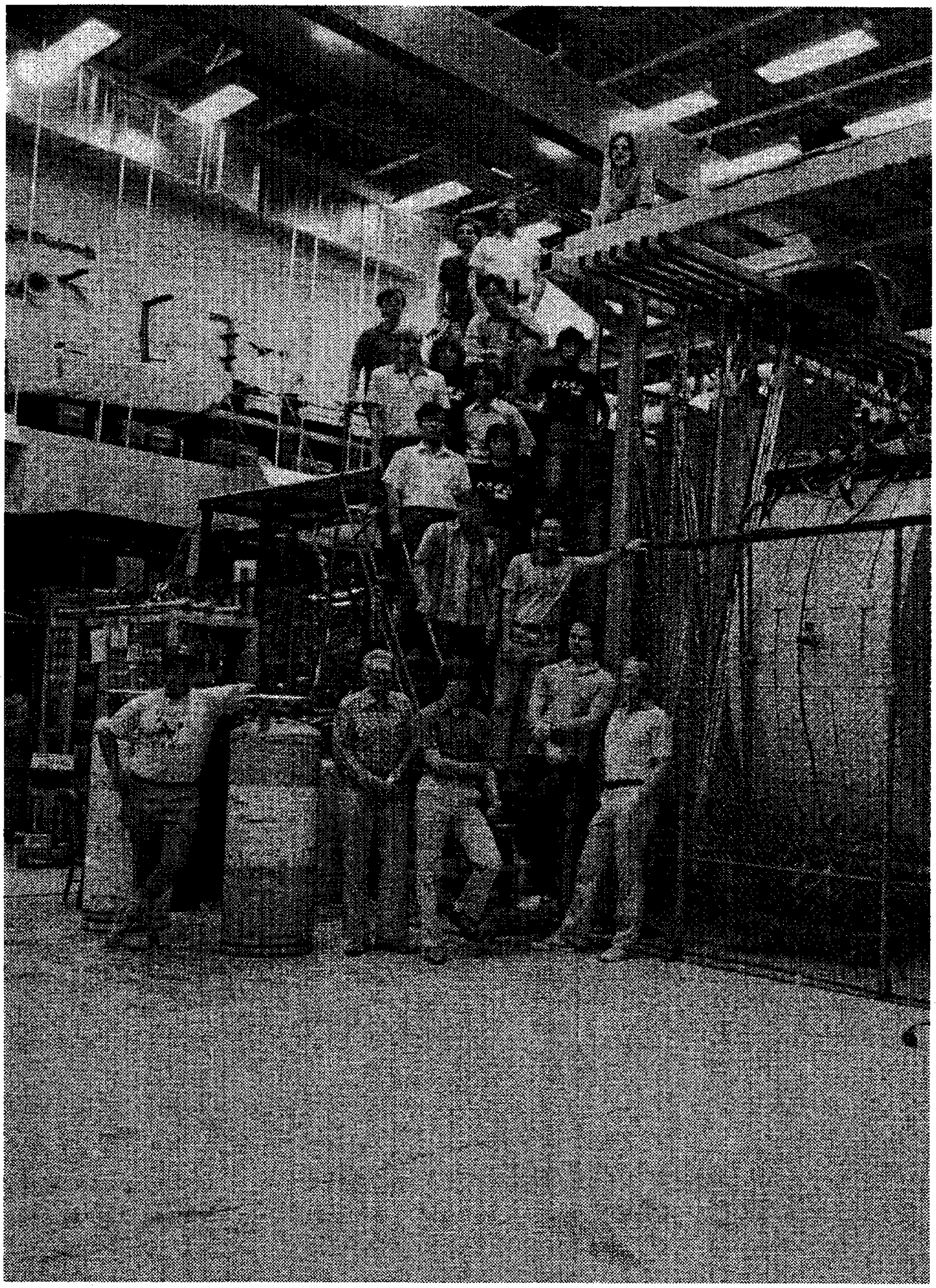

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Measurement of the Relative Branching Fraction $\Gamma(D^0 \to K\mu\nu)/\Gamma(D^0 \to \mu X)$

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The fraction f of D^0 semimuonic decays which occur through the $K\mu\nu$ mode has been measured in a hybrid emulsion spectrometer. Analysis of 124 semimuonic D^0-decay candidates gives $f = 0.32 \pm 0.05(\text{stat}) \pm 0.05(\text{syst})$. From this measurement and existing data on the D^0 semileptonic branching ratio and lifetime, we obtain the branching ratio $R(D^0 \to K^-\mu^+\nu) = (2.4 \pm 0.4 \pm 0.5)\%$ and partial decay rate $\Gamma(D^0 \to K^-\mu^+\nu) = (5.6 \pm 0.9 \pm 1.2) \times 10^{10}\ \text{s}^{-1}$.

PACS numbers: 13.20.Fc, 14.40.Jz

Semileptonic decays of charm are interesting because they appear to be relatively straightforward to calculate.[1-6] The simplest such process is the pseudoscalar decay[7] $D \to Kl\nu$. Data on the partial rate for this decay have been used in some models[1,3,4] to fix parameters for calculating other rates such as that for $D \to K^* l\nu$, which is expected to be roughly equal to that for $K\mu\nu$. The $Kl\nu$ rate has recently been measured in two ways: (1) by comparing[8] the yield of $D^0 \to K^-e^+\nu$ to that of $D^0 \to K^-\pi^+$ for photoproduced D^0's tagged by charged D^*'s, and (2) by measuring[9] the yield of $D^0 \to K^-e^+\nu$ in a sample of tagged charm pairs produced in e^+e^- collisions. We present here the results of a complementary measurement of the fraction f of all D^0 semimuonic decays which occur through the $K^-\mu^+\nu$ mode.

The data were taken in the first run of Fermilab Ex-

5.4 E672 - HADRONIC FINAL STATES IN ASSOCIATION WITH HIGH MASS DIMUONS

Fermilab, IHEP/Protvino (Russia), Illinois/Chicago, Indiana, Louisville, Michigan/Flint

The production of beauty quarks in hadronic collisions is a subject of persistent theoretical and experimental interest. The comparison of the measured beauty-quark production cross section with the Next-to-Leading Order Quantum Chromodynamic (NLO QCD) calculations reveals the underlying dynamics. In addition to the lowest order beauty quark-antiquark pair production processes via gluon fusion or quark exchange, sizable contributions come from diagrams including the gluon exchanges with subsequent gluon splitting, and flavor excitation in which a gluon virtual fluctuation to a beauty quark-antiquark pair is put on-mass shell by an interaction. It is known that the measured inclusive beauty-quark cross sections at the Tevatron collider exceed the NLO QCD predictions by a factor of about 2.5 to 3. The NLO QCD calculations for the beauty quark-antiquark pair production are expected to be more reliable at fixed-target energies.

Renewed interest in the charmonium and bottomonium production originated with the observation by the CDF Collaboration that the direct J/ψ and $\psi(2S)$ production exceeds expectations based on the color singlet model (CSM) of charmonium production by a factor of about 50. This observation led to a development of the color octet model (COM), nonperturbative parameters of which were fitted to match the CDF data. In the color singlet model, the charmonium meson retains the quantum numbers of the produced charm quark-antiquark pair, and thus each J/ψ state can only be directly produced via the corresponding hard scattering color singlet subprocess. The color octet mechanism extends the color singlet approach by taking into account the production of charm quark-antiquark pairs in a color octet configuration accompanied by a gluon. The color octet state evolves into a color singlet state via emission of a soft gluon. The inclusion of the color octet mechanism leads to a prediction that directly produced ψ charmonia will be increasingly transversely polarized at high transverse momentum. The polarization prediction is the most likely effect to help distinguish the COM model from the multiple soft gluon exchanges (color evaporation) model.

E672 was an open geometry experiment, the aim of which was to study hadronic processes yielding high-mass dimuons (the trigger) and associated particles, using proton and pion beams at momenta up to 800 GeV/c striking various nuclear targets. The specific goals, which are all related to experimental tests of Quantum Chromodynamics (QCD), included hadroproduction of: (i) beauty quarks observed through inclusive and exclusive decays to J/ψ, (ii) charmonium χ_c states observed via their radiative decays into $J/\psi\ \gamma$, and (iii) $\psi(2S)$ states observed in its $\mu^+\mu^-$ and $J/\psi\ \pi^+\pi^-$ decay modes.

Experiment E672 shared the Meson West beamline and spectrometer with the experiment E706 studying direct photon production. The data from the two experiments were written to shared tapes, and then independently analyzed. Most of the E672 publications were joint publications with E706 colleagues.

E672 measured beauty-quark production in pion-beryllium collisions at 515 GeV/c by identifying events with J/ψ originating from secondary vertices. In addition to inclusive $J/\psi + X$ decays, the experiment reported five events of exclusive $J/\psi\ K$ or $J/\psi\ K^*$ decays. The measured cross section, although with a large uncertainty, indicated an excess of data over the theory predictions.

E672 studied charmonium production in pion-beryllium and proton-beryllium collisions at 515 GeV/c and 800 GeV/c. The results included differential J/ψ cross sections and fractions of J/ψ produced either directly or as products of $\psi(2s)$ and radiative χ_1 and χ_2 states decays. The measured x_F distributions were used for an extensive comparison with the color-octet model predictions. All values of the required non-perturbative matrix elements were derived from other experiments, primarily from charmonium photoproduction data and from J/ψ production data from the Tevatron. In general, the parameter-free predictions of the model for x_F - distributions agree with the proton and pion induced data both in magnitude and shape. On the other hand, the E672 data are consistent with unpolarized J/ψ production, contrary to expectations from the color octet model, but in agreement with the color evaporation model.

In addition, E672 was one of the first experiments to analyze the absorption of J/ψ particles in nuclear matter.

In its earlier incarnation (1984), E672 was also concerned with the production of jets in 800 GeV/c proton-nucleus interactions. There are several reasons for studying such interactions. First, measurements of secondary particles produced in these processes can provide unique information about the space-time development of proton-nucleon interactions. The nucleus serves as a short-range detector which interferes with the intermediate hadronic state produced in the primary proton-nucleon interaction, before that state can materialize into the observed particles. Second, results from proton-nucleus interactions help in understanding the properties of nuclear matter at high energy densities, a topic of considerable interest for the current quark-gluon plasma investigations.

The E557/E672 trigger required a deposition of large transverse energy (E_T) in a large coverage calorimeter centered around 90 degrees in the proton-nucleon center of mass system. The experiment observed a nuclear enhancement in producing events with large E_T and studied its dependence on the event topology. We were also able to separate effects associated with the jet production from nuclei.

E672 Degree Recipients

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E557/E672 Publications

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E672/E706 Publications

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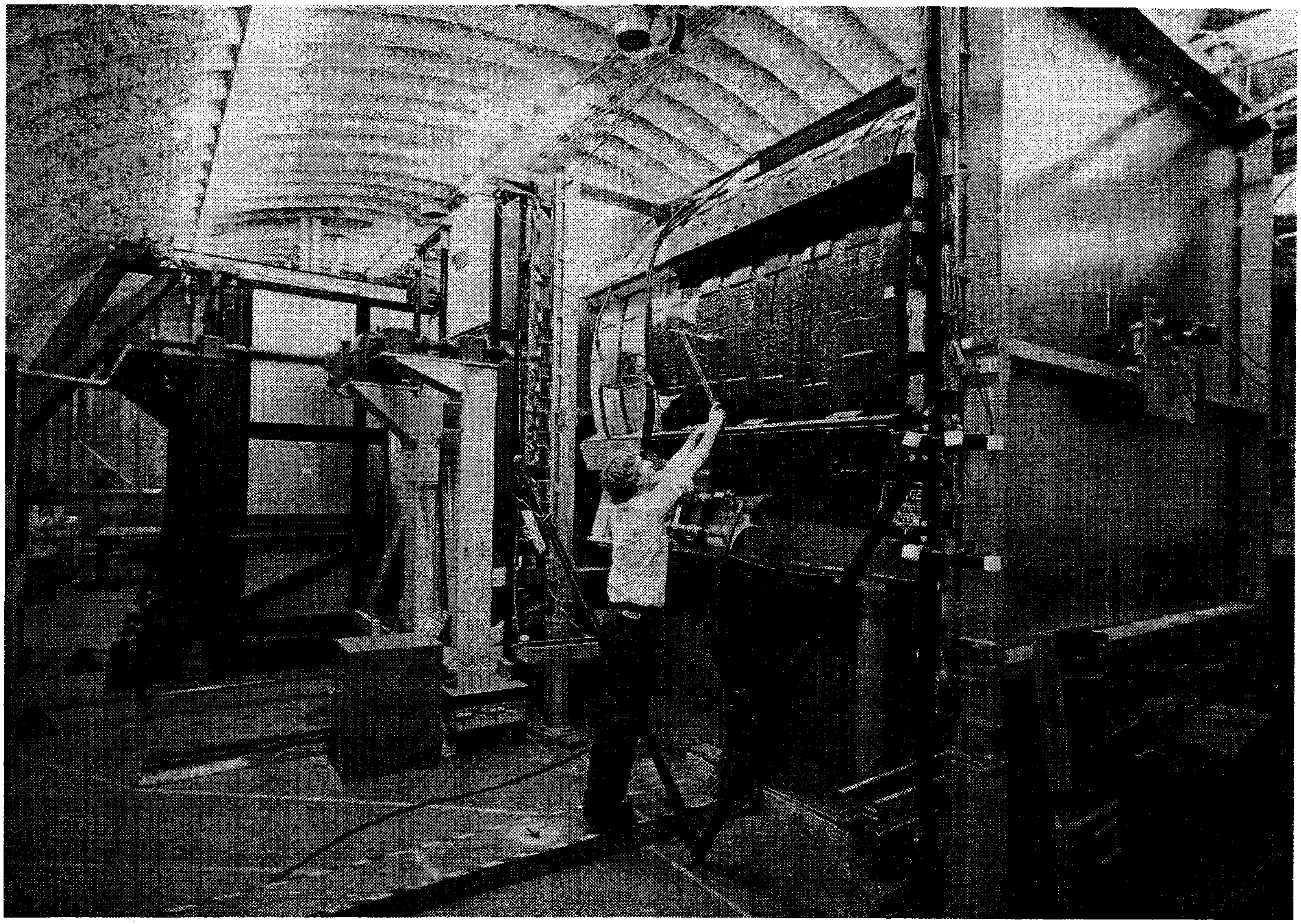

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Production of Charmonium States in π^-Be Collisions at 515 GeV/c

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We report on χ_{c1} and χ_{c2} production in the Feynman-x range $0.1 < x_F < 0.8$ in 515 GeV/c π^-Be collisions. The χ_c states are observed via their radiative decays into J/ψ's. The resulting photons are detected either as showers in the electromagnetic calorimeter or after conversion in the target as e^+e^- pairs in the tracking system. The fraction of J/ψ production due to χ_{c1} and χ_{c2} decays is $0.443 \pm 0.041 \pm 0.035$. The ratio of the χ_{c1} to χ_{c2} cross section is $0.57 \pm 0.18 \pm 0.06$. Our results on J/ψ, $\psi(2S)$, and χ_c production indicate that $0.454 \pm 0.044 \pm 0.042$ of J/ψ's are produced directly. [S0031-9007(96)01608-0]

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Studies of charmonium production in hadron collisions provide important information on both perturbative and nonperturbative QCD. Recent advances in the understanding of quarkonium production have been stimulated by the unexpectedly large cross sections for direct J/ψ and $\psi(2S)$ production at large p_T measured at the Fermilab Tevatron [1]. Three types of models have been used to describe charmonium formation [2]: the color-evaporation model [3,4], the color-singlet model [5,6], and the color-octet model [7,8]. In the color-evaporation model, the directly produced charmonium meson is not constrained to the same J^{PC} state as the $c\bar{c}$ pair produced in the hard scatter because of the emission of soft gluons during the meson's formation. In the color-singlet model, the charmonium meson retains the quantum numbers of the produced $c\bar{c}$ pair, and thus each J^{PC} state can only be directly produced via the corresponding hard scattering color-singlet subprocesses. The color-octet mechanism extends the color-singlet approach by taking into account the production of $c\bar{c}$ pairs in a color-octet configuration accompanied by a gluon. The color-octet state evolves into a color-singlet state via emission of a soft gluon. These models of charmonium formation lead to different expectations for the production rates of the charmonium states. This Letter presents data on the production of these states in π^- nucleon collisions at a significantly higher $\sqrt{s}$ than previously available.

The experiment was performed in the Fermilab Meson West beam line using a large-aperture, open-geometry spectrometer [9,10]. A 515 GeV/c beam was incident on Be and Cu targets. Only π^-Be interactions, which represent 85% of the dimuon triggers and an integrated luminosity of 7.5 pb^{-1} per nucleon, are discussed in this Letter. The $\mu^+\mu^-$ mass distribution is shown in Fig. 1. A fit yields $7750 \pm 90 \pm 60$ J/ψ's with a FWHM mass resolution of 130 MeV/c^2 [11] and a mean J/ψ mass

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5.5 E687 - PHOTOPRODUCTION OF CHARM AND BEAUTY

INFN/Bologna (Italy), UC/Davis, Colorado, Fermilab, INFN/Frascati (Italy), Illinois, Korea (Korea), INFN/Milano (Italy), Milano (Italy), North Carolina, Northwestern, Notre Dame, Pavia (Italy), Puerto Rico/Mayaguez, South Carolina, Tennessee, Western Kentucky, Vanderbilt

Experiment E687 was an experiment studying the production and decay of charm particles in the Wideband Photon Beam in the Proton Area. The spectrometer was based on two large analysis magnets, which provided a large charged particle acceptance covering the entire forward hemisphere. The spectrometer was instrumented with twelve planes of silicon microstrip detectors, totaling 8256 pulse height analyzed strips, which provided primary and secondary vertex reconstruction; three threshold Cerenkov counters of about 100 cells each to provide charged hadron identification; a 10 meter neutral Vee decay volume; small and wide angle electromagnetic calorimeters providing excellent γ and π^0 identification; and muon identification based on scintillators and proportional tubes. Hadron calorimeters permit one to trigger on photoproduced events with hadrons in the final state.

The E687 Collaboration had three data-taking periods. The first occurred from December 1987- February 1988. During this period a total of 60 million triggers were written on tape. The second running period was from March 1990 until August 1990, when 300 million events were accumulated. The third running period began in June 1991 and lasted until January 1992. During this third running period we accumulated another 200 million triggers giving the experiment a total of 500 million triggers for the 1990-1991 running period.

This experiment had many important results, including obtaining the best lifetime measurements for all of the weakly decaying charm particles, D^+, D^o, D_s, Λ_c, Ξ_c^+; the discovery of the Ω_c^0; charm baryon and measurement of its lifetime; and detailed study of the semileptonic form factors of D^o, D^+, *and* D_s. Many of the measurements made by the E687 collaboration remain as the defining numbers in the compilations of the Particle Data Group.

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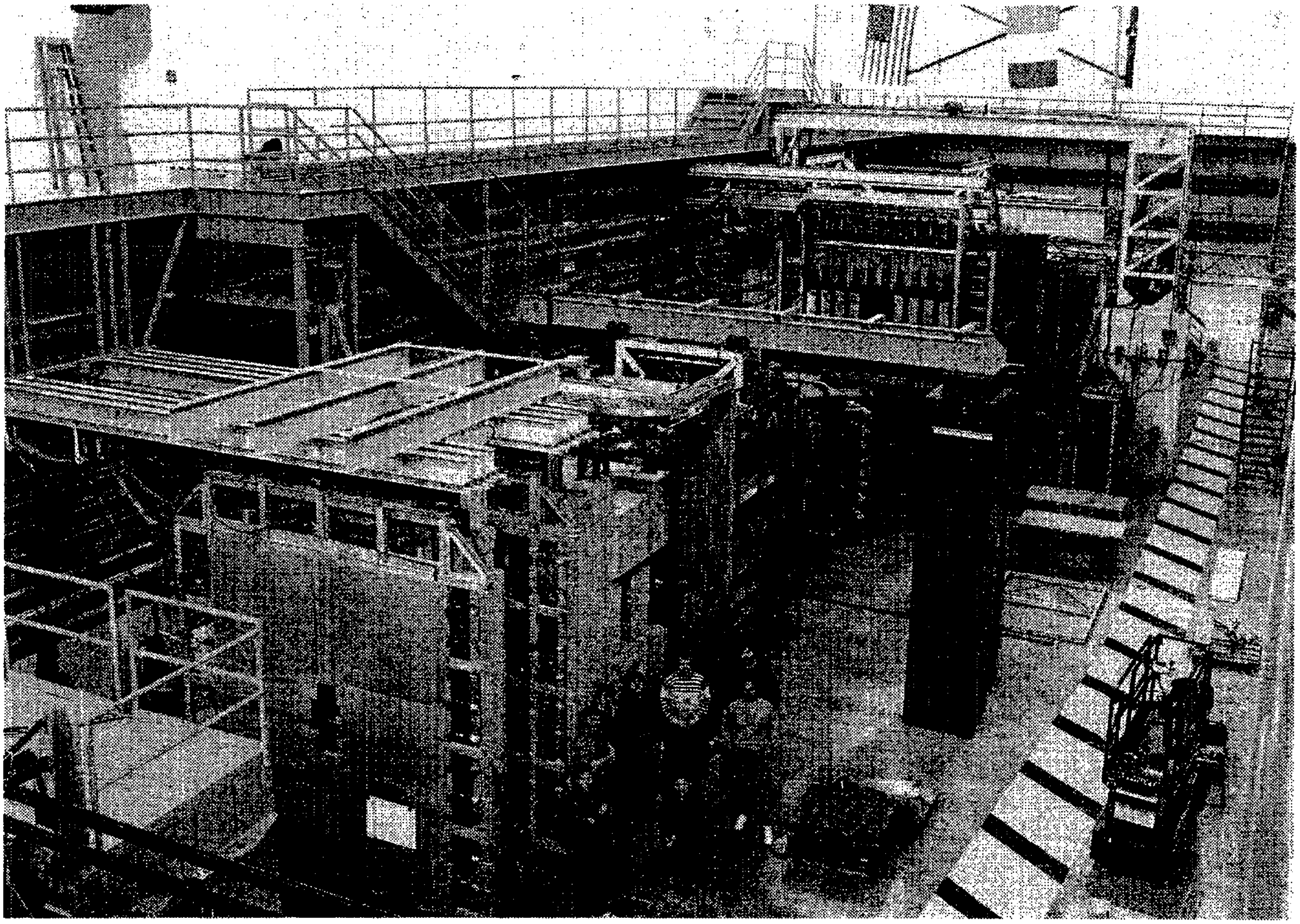

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Measurement of the Λ_c^+ Lifetime

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A precise measurement of the Λ_c^+ lifetime using approximately 1340 fully reconstructed $\Lambda_c^+ \to pK^-\pi^+$ and charge conjugate decays is presented. The data were accumulated by the Fermilab high energy photoproduction experiment E687. The lifetime of the Λ_c^+ is measured to be $0.215\pm0.016\pm0.008$ ps.

PACS numbers: 14.20.Kp, 13.30.Eg

This paper reports a new measurement of the Λ_c^+ lifetime using approximately 1340 fully reconstructed $\Lambda_c^+ \to pK^-\pi^+$ decays. Throughout this paper, the charge conjugate state is implied when a decay mode of a specific charge is stated. Previous measurements have been limited to samples of ≈ 100 or fewer Λ_c^+ decays. Because of the relatively large sample of Λ_c^+ decays, extensive consistency checks of the results and a detailed systematic study can be made. Comparisons of accurate measurements of the Λ_c^+ lifetime with those of other charm baryons and mesons provide information on the relative sizes of the different decay contributions: spectator decay, W exchange, and the interference of identical light quarks in the final state [1].

The data for this analysis were collected in 1990 and 1991 in the Fermilab wideband photoproduction experiment E687. The E687 detector is described in detail elsewhere [2].

The Λ_c^+ decays were reconstructed by a *candidate driven* method [2]. The efficiency of this algorithm in finding vertices is essentially independent of the primary and secondary vertex separation, and so this method should not create a bias in the lifetime measurement.

Information from the Čerenkov counters is used to select protons, kaons, and pions. The confidence level at which the three microstrip tracks of the $pK^-\pi^+$ combination form a vertex will be labeled CLD. The confidence level at which any of the three $pK^-\pi^+$ tracks extrapolate back to the primary vertex is labeled CL1. The confidence level at which other microstrip tracks not already assigned to either the primary or secondary vertices point back to the secondary vertex is labeled CL2. The number of background $pK^-\pi^+$ combinations can be greatly reduced by cuts on CL1 and CL2. The drawback is that

5.6 E691 - CHARM PRODUCTION WITH THE TAGGED PHOTON SPECTROMETER

UC/Santa Barbara, Carleton (Canada), CBPF (Brazil), Colorado, Fermilab, NRC (Canada), Oklahoma, Sao Paulo (Brazil), Toronto (Canada)

E691 was the first experiment to clearly establish the power of fixed target experiments in the study of heavy quark physics. The 100 million event data set led to physics publications using over ten thousand reconstructed charm decays. Many of the measurements from this charm quark experiment dominated the world averages of relevant parameters for over a decade. The measurements of charm particle lifetimes, which were among the first results published by the experiment, genuinely established the reputation of the experiment. Later papers in refereed journals covered topics relating to tests of the Standard Model, determination of the mechanisms of the electroweak decay of charm particles, QCD measurements, etc.

The first publication from E-691 was of the A-dependence of J/ψ photoproduction. This data was taken in a special closed geometry period at the end of the run. Precision measurements of the lifetimes of charm mesons and the lowest mass charm baryon, from data taken with the standard open geometry spectrometer used during most of the run, followed soon after. These lifetime measurements, along with a wealth of branching ratios, serve as the basis of understanding the dynamics of charm quark decay, selecting among spectator, W exchange, annihilation and penguin theoretical diagrams in the hadronic decay sector. The measurements in the semileptonic domain include the first full Dalitz plot analysis in terms of all the kinematic variables available. This became possible only with the size of the data set and good signal to background results obtained after event selection. Tests of the Standard Model have included searches for D^o anti-D^o mixing and flavor changing neutral currents in leptonic decays of D^o's.

The most copious signals were used to study the charm production mechanism, dominated by photon-gluon fusion. The data, interpreted with next to leading order calculations recently available, led to determination of such fundamental parameters as the mass of the charm quark and the most direct determination of the distribution of gluons in nucleons.

E691 was the first Tevatron experiment using the Tagged Photon Spectrometer (TPS), a multi-stage full acceptance detector with precision determination of charged particle tracks and particle identification. The TPS tracking had been specially upgraded for E691 with the introduction of nine silicon microstrip detectors downstream of the 5 cm beryllium target. These detectors, each with 50 micron-wide detector elements, supplied the capability of resolving the decay vertex from the primary production point of long-lived charm particles. This permitted events with charm particles to be selected from the much more copious, but less interesting background events. In addition, by using only those tracks which came from the decay vertex, the combinatoric background was enormously reduced.

The trigger for the experiment was a very general high-Et trigger. This allowed accumulation of data for the wide variety of physics which has come out of the experiment. The Tevatron itself provided upgraded capability relative to earlier experiments. The higher energy allowed greater photon fluxes in the incident beam and the improved spill duty factor (longer beam availability times) allowed collection of the unprecedented amount of data. Finally, the experiment benefited from the availability of the first parallel processing computing system applied to a Fermilab experiment. This system incorporated home-built (non-commercial), single-board computers (the first ACP farms). Use of this system significantly sped up the reconstruction of raw data to allow early results with the full data set.

E691 pioneered techniques which have since become standard in a very broad range of high energy physics experiments, especially the use of silicon microstrip detectors in Fermilab experiments and of parallel processing for off-line reconstruction of data.

E691 Degree Recipients

Thomas Earl Browder	Ph.D.	University of California at Santa Barbara
Jean Etienne Duboscq	Ph.D.	University of California at Santa Barbara
Mark Gibney	Ph.D.	University of Colorado
Jenny Huber	Ph.D.	University of California at Santa Barbara
Jose Guilherme Lima	M.S.	Centro Brasileiro de Pesquisas Fisicas
Scott Menary	Ph.D.	University of Toronto
Gregory Dean Punkar	Ph.D.	University of California at Santa Barbara
Johannes Rudolf Raab	Ph.D.	University of California at Santa Barbara
William Robert Ross	Ph.D.	Yale University
David Schmidt	Ph.D.	University of California at Santa Barbara
Anthony Lee Shoup	Ph.D.	University of Cincinnati
Daniel James Sperka	Ph.D.	University of California at Santa Barbara
Audrius Stundzia	Ph.D.	University of Toronto

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Measurement of the D^0, D^+, and D_s^+ lifetimes

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We have measured the lifetimes of the D^0, D^+, and D_s^+ mesons which were produced by a high-energy photon beam incident on beryllium. Using the Fermilab Tagged Photon Spectrometer with a silicon-microstrip vertex detector we have collected 10^8 events from which we have extracted about 4200 D^0 decays in the $K^-\pi^+$ and $K^-\pi^+\pi^-\pi^+$ modes, 3000 D^+ into the $K^-\pi^+\pi^+$ channel, and a total of 230 D_s^+ into $\phi\pi^-$ and $\bar{K}^{*0}K^+$. From an analysis of these events we have determined the lifetimes for the D^0, D^+, and D_s^+ to be $0.422\pm0.008\pm0.010$, $1.090\pm0.030\pm0.025$, and $0.47\pm0.04\pm0.02$ psec, respectively.

I. INTRODUCTION

The singly charmed D^0, D^+, and D_s^+ mesons provide a unique opportunity to study the weak decays of the charm quark. Since the surprising discovery of different D^0 and D^+ lifetimes,[1] much theoretical and experimental work has been devoted to explaining and to obtaining better measurements of that difference. The lack of high-statistics data on charm lifetimes has impeded the development of realistic theories and their corresponding tests. Precise measurements of the D^0, D^+, and D_s^+ lifetimes provide important constraints on the various theoretical models of charm decay.

The obstacles to precise measurements of charmed-particle lifetimes have been a combination of low statistics, poor signal-to-noise ratios, and poor vertex resolution.[2] However, using the Tagged Photon Spectrometer (TPS) and silicon-microstrip detectors (SMD's) we have collected a large charm-rich data sample in experiment 691 (E-691) at Fermilab. We have extracted approximately 4200 D^0 decays in three modes, 3000 D^+ decays in a single channel, and 230 D_s^+ events in two modes. (Throughout this paper the charge-conjugate states are implicitly included.) In this paper we present our final results[3] from the lifetime analysis of these events.

In Sec. II of this paper we describe the apparatus and in Sec. III the event reconstruction. The common elements in the event selection for the different modes are given in Sec. IV. The method of extracting the lifetimes and the details particular to each mode are presented in Sec. V. A discussion of systematic errors follows. In Sec. VII we summarize our results and compare them to theoretical calculations.

II. EXPERIMENTAL APPARATUS

The TPS is a large-acceptance two-magnet spectrometer which was designed and built for a previous experiment, E-516 (Ref. 4). The upgraded version of the spectrometer as used by E-691 is shown in Fig. 1.

The photon beam was generated from the bremsstrahlung of 260-GeV/c electrons as they passed through a 0.2-radiation-length tungsten radiator. A set of magnets behind the radiator deflected the electrons into an array of shower counters where the final electron energy was measured. From this measurement and the electron beam energy, the radiated photon energy k was deduced. The photon energy spectrum extended from 90–260 GeV, and was roughly $1/k$ from 100 GeV on; the mean tagged photon energy was 145 GeV.

The most significant improvement to the TPS for the E-691 run was the installation of a vertex detector assembly.[5] We used nine silicon-microstrip detector planes with a 50-μm strip spacing. As shown in Fig. 2, the planes were arranged telescopically and alternately covered one of the three views, X (0°), Y (90°), and V (−20.5°). The angular acceptance of the system was about ±100 mrad. The signals from the strips were amplified, and discriminated at about half of the signal level produced by a minimum ionizing particle. We used modified multiwire-proportional-chamber (MWPC)

5.7 E743 - CHARM PRODUCTION IN PP COLLISIONS WITH LEBC-FMPS

Achen (German), ihep / berlin (Germany), CERN (Switzerland). Strasbourg (France), Dunke, Fermilab, Flordia State, Kansas, L'Etat (Belgium), Libre (Belgium), LPNHE (France), Michigan State, Northeastern, Notre Dame, Tata (India), Vanderbilt, Vienna (Austria)

The small liquid hydrogen bubble chamber LEBC was specially designed for the study of charm particle properties in the fixed target environment. The conventional optical system of LEBC provided a resolved bubble diameter of 20 microns which yielded a high efficiency for the detection of both production and decay vertices of the charm particles. LEBC was built at CERN and first used there with the European Hybrid Spectrometer in experiments with 360 GeV/c pion and 400 GeV/c proton beams.

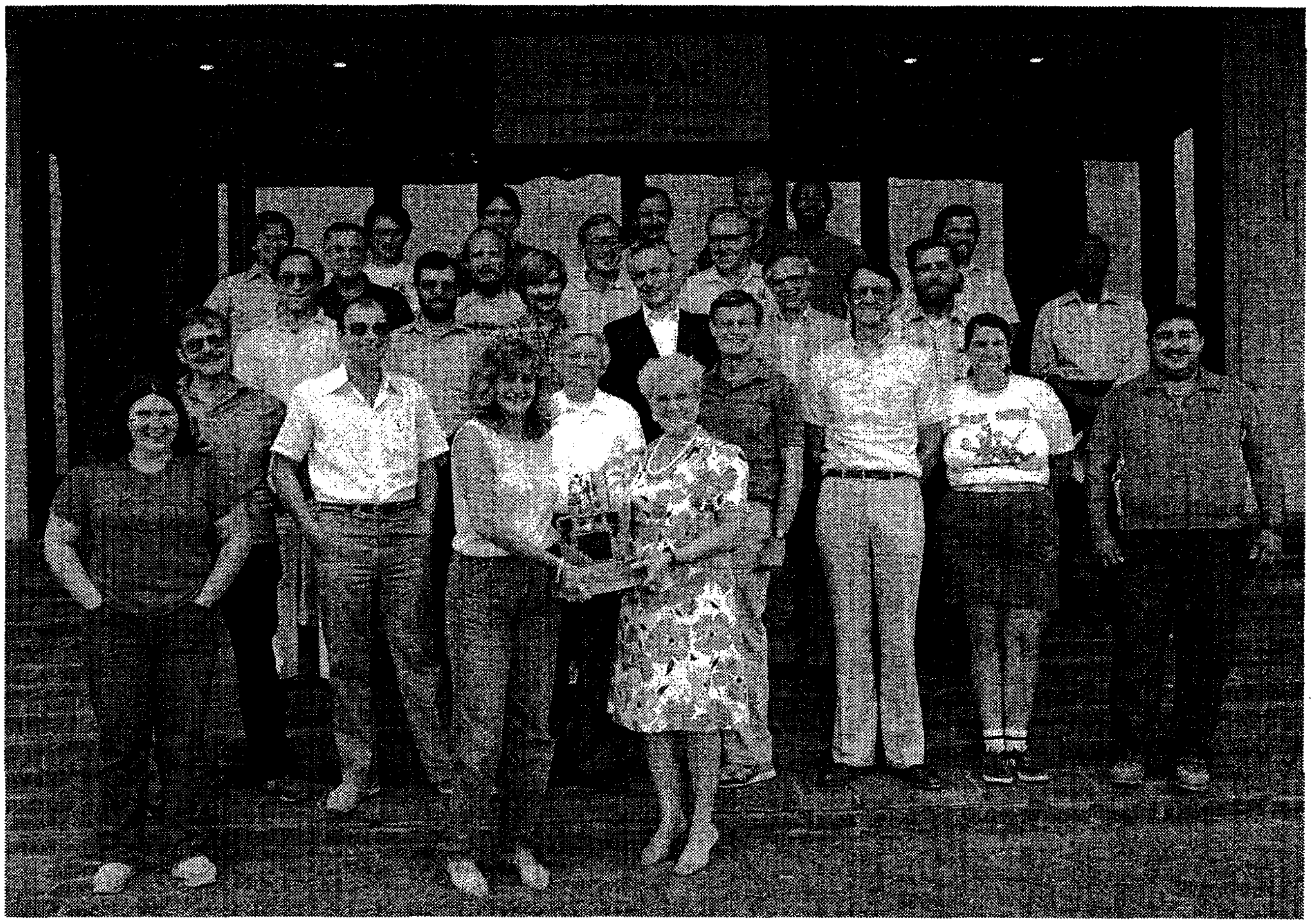
Charm production was an exciting research topic in the early eighties. CERN experiments using the ISR were obtaining indirect evidence for charm hadroproduction and their attempts at cross section determinations yielded values between ten and a hundred times larger than those of the LEBC experiment. Was there a threshold for new physics between the LEBC and ISR energies? The Fermilab Tevatron 800 GeV proton beams gave a natural way to investigate the issue. An 800 GeV proton beam colliding with a proton at rest gives a center-of-mass energy half way between the LEBC 400 GeV pp data and the ISR colliding-beam data, and it was therefore decided to propose an experiment at Fermilab using LEBC married to a suitable Fermilab spectrometer. Of course, this was a lot easier said than done!

LEBC was a plastic disposable bubble chamber occupying about a cubic foot of space and it was easy to bring LEBC to Fermilab for the PAC presentation in 1983. "At last a table-top particle physics experiment," said Leon Lederman, and the experiment was rapidly approved. The Fermilab MPS spectrometer was chosen for downstream particle identification and momentum determination. Several tons of equipment and a team of European technicians and engineers arrived from CERN, and it was quite a challenge to have everything up and running for the Tevatron start-up in 1985. Some of the more unexpected problems encountered by the collaboration included living creatures in the Casey's pond cooling water, spilled liquids on the scanning table causing experimenters to stick to the table top in their eagerness to find charm events, but great excitement over all.

By all measures, the experiment was a success. Almost 1.2 million triggers were recorded, corresponding to 0.5 million pp interactions in the visible region of the liquid hydrogen. More than a hundred charm event candidates were discovered and these were used to measure charm production characteristics. These results supported the CERN LEBC results and indicated problems with the ISR data. All results were in good agreement with the QCD-based fusion model.

Finally, a comparison of the production characteristics of charm events in the hadroproduced CERN and Fermilab data were used to give a somewhat controversial determination of the charm quark mass.

The experiment was a huge amount of fun, didn't cost much, and produced valuable physics results. What more can one ask for?



E743 Degree Recipients

Gay E. Canough	Ph.D.	Notre Dame University
T.O. Dershem	Ph.D.	University of Michigan
C. Hamilton	Ph.D.	Northeastern University
Xiao D.James Liu	Ph.D.	University Kansas
G.E. Mendez	Ph.D.	Duke University
Ai Gia Nguyen	Ph.D.	Michigan State University
A. Roth	Ph.D.	Aachen University
Mark Frederick Senko	Ph.D.	Vanderbilt University
B. Vonck	Ph.D.	Brussels University
Michael F. Weber	Ph.D.	University of Michigan
C.F. Wild	Ph.D.	Duke University
Christos Zabounidis	Ph.D.	Northeastern University

E743 Publications

D-Meson Production in 800 GeV/c p p Interactions., R. Ammar, *et al.*, Phys.Rev.Lett. **61**, 2185 (1988).
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D-Meson Production in 800-GeV/*c* *pp* Interactions

R. Ammar,[1] R. C. Ball,[2] S. Banerjee,[3] P. C. Bhat,[4] P. Bosetti,[5] C. Bromberg,[6] G. E. Canough,[7] T. Coffin,[2] T. O. Dershem,[2] R. L. Dixon,[8] H. C. Fenker,[8] S. N. Ganguli,[3] U. Gensch,[9] P. Girtler,[14] A. T. Goshaw,[4] F. Grard,[10] A. Gurtu,[3] C. Hamilton,[11] V. P. Henri,[10] J. J. Hernandez,[12],[a] J. Hrubec,[1] M. Iori,[12],[b] L. W. Jones,[2] D. Kuhn,[14] D. Knauss,[9] I. D. Leedom,[11] P. Legros,[10] J. Lemonne,[13] H. Leutz,[12] X. Liu,[1] P. K. Malhotra,[3] J. M. Marraffino,[15] G. E. Mendez,[4] R. Miller,[6] T. Naumann,[9] A. Nguyen,[6] H. Nowak,[9] P. Pilette,[10] J. Poirier,[7] A. Poppleton,[12] R. Raghavan,[3] K. Rasner,[14] S. Reucroft,[11] W. J. Robertson,[4] B. P. Roe,[2] A. Roth,[5] M. Senko,[15] W. Struczinski,[5] A. Subramanian,[3] M. C. Touboul,[12],[c] B. Vonck,[13] L. Voyvodic,[8] J. W. Waters,[15] M. F. Weber,[2] M. S. Webster,[15] and C. Zabounidis[11]

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We report on a study of the inclusive production properties of $D/\bar{D}$ mesons in *pp* collisions at 800 GeV/*c* and compare our results to measurements made at lower energies and to the expectations of the QCD fusion model.

PACS numbers: 13.85.Ni, 14.40.Jz

Charm particle production in hadronic collisions has proven to be a useful test of the QCD parton-fusion model.[1] The model predicts an increase of the charm production cross section by about a factor of 3 between $\sqrt{s} \approx 26$–27 GeV and $\sqrt{s} \approx 53$–63 GeV while comparison of CERN-Super Proton Synchrotron (SPS) fixed-target experiments and CERN-Intersecting Storage Ring (ISR) experiments indicates a cross-section increase of at least a factor of 10.[2] Mechanisms other than the fusion model were invoked to explain this large increase in the charm cross section.[3] Recently this experiment, a study of charm production in *pp* reactions at 800 GeV/*c* ($\sqrt{s} = 38.8$ GeV) using the precision vertex detector LEBC (Lexan bubble chamber) filled with liquid hydrogen followed by a multiparticle spectrometer (Fermilab MPS), has reported a cross section consistent with an energy dependence for charm production in agreement with fusion-model predictions.[4] Those results used the topological uniqueness of charm decays, as seen in a hydrogen target and detector, to identify the data sample and thus involved only the LEBC data. Here we report on our measurements of the *D* meson x_F and $p_\perp$ behavior as determined from both the LEBC and the spectrometer data and compare them to the predictions of the fusion model.

We note that, in the absence of a well accepted procedure for correcting the nuclear effects, hydrogen target data taken with this chamber are the most reliable source of information on inclusive charm particle production in *pp* collisions.

The data were obtained during the third fixed-target running period of the Fermilab Tevatron accelerator. The LEBC-MPS apparatus was exposed to 800-GeV/*c* protons in the MT beam line. LEBC served both as a liquid-hydrogen target and as a high-resolution vertex detector upstream of the MPS. The chamber was operated so as to produce bubbles of 20 μm diam and a bubble density of 80 cm^{-1}. Two high-resolution proportional wire chambers positioned immediately downstream of the LEBC generated an interaction trigger

5.8 E769 - HADROPRODUCTION OF CHARM

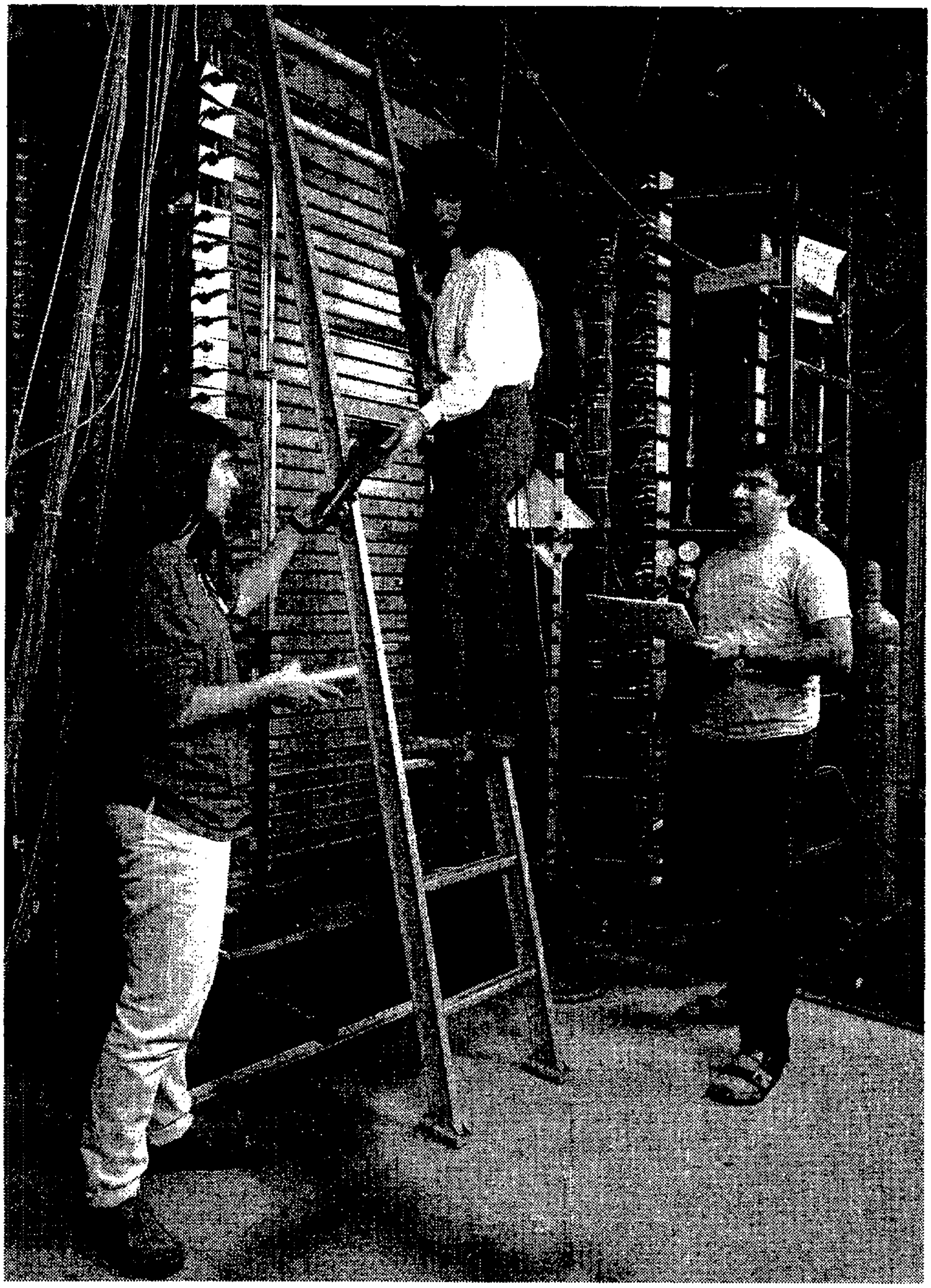
CBPF (Brazil), Fermilab, University of Mississippi, Northeastern University, University of Toronto (Canada), Tufts University, University of Wisconsin - Madison, Yale University

In interactions involving hadrons such as pions, kaons, and protons, the production of charm particles arises dominantly from the fusion of the glue that holds the incident hadrons together. Thus, by studying the charm production process itself, we have obtained information about the glue inside pions, kaons, and protons. E769 demonstrated conclusively, that the glue in mesons, pions and kaons, is distributed differently from that in protons. The glue in mesons is "harder" than it is on average in protons. This might be expected since the glue in mesons binds a quark and an antiquark together, whereas in protons, the glue must be spread among three quarks.

E769 successfully applied, for the first time, the tools which had been used so effectively in the previous charm quark experiment with photon beams, to the hadron beam environment. Those tools included "silicon microstrip detectors" placed very close to the experiment production target for precise determination of the trajectories of charged particles and the separation of events with charm particles from the thousand-times more copious less-interesting interactions. Secondly, recently-available new computing technologies were applied to what were at the time revolutionary amounts of data. These technologies involved the application of parallel processing in both data acquisition and off-line data processing. E769 additions which were specially relevant for this hadron-beam experiment were two devices, each sensitive to a different kind of light emitted when beam particles passed through particular kinds of material. These devices were used to identify the incident beam particles as pions, kaons, or protons one-by-one. The two kinds of light are called transition radiation and Cerenkov radiation. The use of all these techniques together allowed E769 to study the production of charm particles by identified mesons and protons in the incident beam, thereby obtaining new results on both the charm particles and the internal structure of the beam particles themselves.

Another example of the kind of information coming from E769 measurements is how quarks produced in high-energy interactions evolve into the particles that are seen in the laboratory. This process, called "fragmentation" and "hadronization", can be understood by studying the regularities and differences among the types of charm particles and anti-particles as they are produced by the pions, kaons and protons.

E769 has shown evidence in several forms for the linkages among the quarks, both charm and more copious varieties, as the evolution unfolds in space and time.



E769 Degree Recipients

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Sandra Amato	Ph.D.	Centro Brasileiro de Pesquisas Fisicas
Juan Astorga	Ph.D.	Tufts University
W. David Dagenhart	Ph.D.	Tufts University
Chris Darling	Ph.D.	Yale University
Pauline Gagnon	Ph.D.	University of California at Santa Cruz
Miriam Gandelman	M.S.	Centro Brasileiro de Pesquisas Fisicas
Colin Gay	Ph.D.	University of Toronto
Robert Jedicke	Ph.D.	University of Toronto
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Helio da Motta	Ph.D.	Centro Brasileiro de Pesquisas Fisicas
Joao R.T. de Mello Neto	Ph.D.	Centro Brasileiro de Pesquisas Fisicas
David Passmore	Ph.D.	Tufts University
Ali Rafatian	Ph.D.	University of Mississippi
Alberto Reis	Ph.D.	Centro Brasileiro de Pesquisas Fisicas
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Dror Trumer	M.S.	Tel Aviv University
Andrew Wallace	Ph.D.	Yale University
Zhongxin Wu	Ph.D.	Yale University

E769 Publications

Feynman-x and Transverse Momentum Dependence of $D^{\pm}$ and D^{o}, anti-D^{o} Production in 250 GeV π^{-}-Nucleon Interactions, G.A. Alves, *et al.*, Phys. Rev. Lett. **69**, 3147 (1992).
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Feynman-x and Transverse Momentum Dependence of D Meson Production in 250 GeV π, K, and p Interactions with Nuclei

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We measure the differential cross sections with respect to Feynman x (x_F) and transverse momentum (p_T) for π, K, and p-induced charm meson production using fully reconstructed D^+, D^0, and D_s decays. The shapes of these cross sections are compared to the theoretical predictions for charm quark production of next-to-leading order perturbative QCD using modern parametrizations of the pion and nucleon parton distributions. We observe the differences expected in production induced by projectiles with different gluon distributions, harder distributions being indicated for mesons than for protons. [S0031-9007(96)01095-2]

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Perturbative QCD predictions of differential cross sections for charm quark production in hadronic collisions depend, through the dominant gluon-gluon fusion process, on the momentum distributions of the gluons in the projectile and target particles [1]. Furthermore, the shapes of these cross sections are relatively insensitive to theoretical uncertainties [2]. Although nonperturbative processes, particularly hadronization, additionally impact the x_F and p_T distributions of charm hadrons, these effects are reasonably assumed to be independent of initial-state gluon distributions. As a consequence, the shapes of these differential cross sections should be sensitive to differences in beam-particle gluon distributions.

In this Letter we report measurements, for π, K, and p beams, of D meson differential cross sections versus x_F and p_T, the latter distributions for $x_F > 0$. Fermilab E769 is the first experiment in which charm production induced by π, K, and p beams is studied at a common beam energy and using a single target and spectrometer. Moreover, few published measurements of charm differential cross-section distributions benefit from full mass reconstruction and identification and momentum determination of secondary particles. In this category, our data set represents a factor-of-2 improvement in the number of π-induced charm decays; for K and p beams, tenfold and threefold increases in statistics, respectively, are realized [3–5]. Note that the distributions presented are absolutely normalized; results on the total forward cross sections of charm particles are presented in the preceding Letter [6].

D meson signals are obtained by combining the decays $D^+ \to K^-\pi^+\pi^+$, $D^0 \to K^-\pi^+$, $D_s^+ \to \phi\,\pi^+$ ($\phi \to K^+K^-$), and $D_s^+ \to \overline{K}^*(892)^0K^+$ ($\overline{K}^{*0} \to K^-\pi^+$). Throughout this paper charge conjugate decays are also implied. Our previously published data for π^- beam [7] have been augmented with π^+ beam data for purposes of comparison with K and p beam results.

The E769 data set was collected using collisions of negatively and positively charged 250 GeV mixed secondary beams on a multifoil target of Be, Cu, Al, and W. Event-by-event tagging, described in [6], allowed identification of the five beam particle types ($\pi^\pm$, $K^\pm$, and p) used in this analysis. Detailed descriptions of the TPL Spectrometer, our on-line triggers, and our off-line event reconstruction and secondary vertex filter are found in [7], and references quoted therein. Analysis cuts were applied to select events with one or more of the aforementioned D decays. These cuts were based on vertex information and the transverse momenta of the decay tracks with respect to the direction of the parent D; this analysis is similar to that presented for D^+ and D^0 decays in a previous paper [7]. In addition, for $D_s \to K^*K$ decays, the absolute

 0031-9007/96/77(12)/2392(4)$10.00

5.9 E771 - BEAUTY PRODUCTION BY PROTONS

Athens (Greece), Brown, UC/Berkeley, UCLA, Duke, Fermilab, Houston, JINR (Russia), Lecce (Italy), MIT, McGill (Canada), Nanjing (PRC), Northwestern, Pavia (Italy), Pennsylvania, Prairie View A&M, Shandong (PRC), South Alabama, SSCL, Vanier (Canada), Virginia, Wisconsin

The last experiment in a Proton Area High Intensity Laboratory sequence was E771. This experiment was designed to detect the production of mesons containing beauty quarks. The beauty (or bottom) equivalent of charmonium, bottomonium or upsilon, had been discovered at Fermilab in the late 70's, but, at the time E771 was being planned, hardly any information was available on the production of mesons containing a beauty quark together with a light (up or down) quark. E771 was designed to observe the production of such particles (B-mesons) via their decays into J/ψ or into two muons (plus other particles). Such a study would shed light on various aspects of QCD. B-meson production occurs in approximately one out of a million interactions of a high energy beam with a target, and a further suppression in the amount of collectable events is caused by the small probability of a B-meson decaying into an easily identified final state (e.g. the one containing two muons). The main result of the experiment was to measure the cross section (i.e. the rate) of B-meson production by 800 GeV protons. Another product of the experiment was to set the best limit for an extremely rare process, "Flavor Changing Neutral Currents", whose observation would clarify fundamental aspects of the weak nuclear force (which is responsible for radioactive beta decay, or, more in general, for the transmutations among quarks of different flavors).

This beauty experiment was made feasible by the increase in energy of the Fermilab accelerator in the early 1980's from 400 to 800 GeV, which made possible the special high intensity secondary beam that was used for E771.

E771 Degree Recipients

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Marco Panareo	Dottorato	University of Bari
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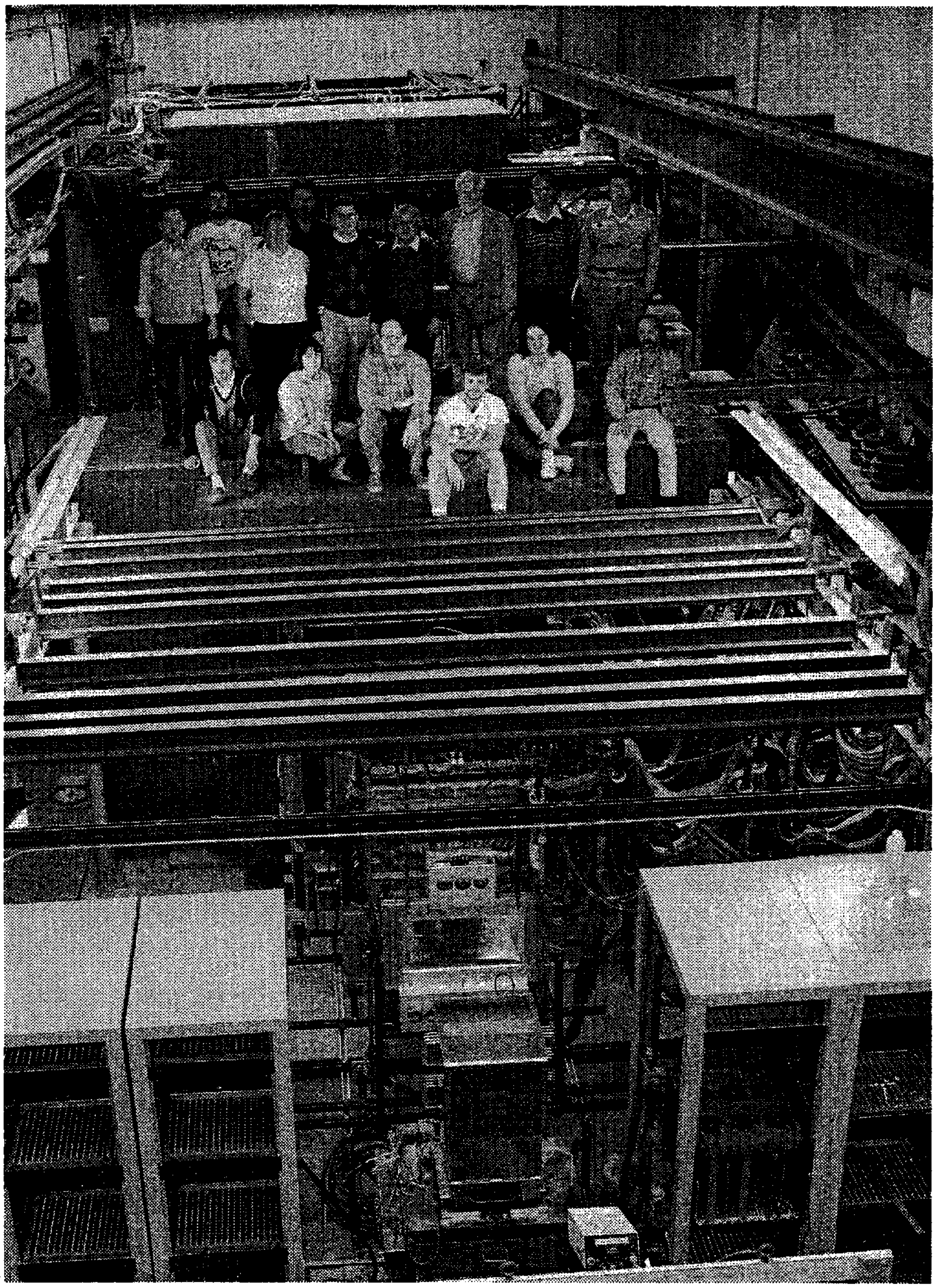

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Production of J/ψ, ψ' and Upsilon in 800 GeV/c Proton-Silicon Interactions., T. Alexopoulos, *et al.*, Phys. Lett. **B374**, 271 (1996).
Search for the Flavor Changing Neutral Current Decay $D^o \rightarrow \mu^+\mu^-$ in 800 GeV/c Proton-Si Interactions., T. Alexopoulos, *et al.*, Phys. Rev. Lett. **77**, 2380 (1996).
Differential Cross Sections of J/ψ and ψ' in 800 GeV/c p Si Interactions., T. Alexopoulos, *et al.*, Physical Review **D55**, 3927 (1997).
A Measurement of the b anti-b Cross Section in 800 GeV/c Proton-Silicon Interactions., T. Alexopoulos, *et al.*, Phys. Rev. Lett. **82**, 41 (1999).
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A Measurement of χ Production in 800 GeV/c p N Interactions., K. Hagan, *et al.*,, submitted to Physical Review **D**, (1999).

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Search for the Flavor Changing Neutral Current Decay $D^0 \to \mu^+\mu^-$ in 800 GeV Proton-Silicon Interactions

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We have searched for the flavor changing neutral current decay $D^0 \to \mu^+\mu^-$ in the dimuon data obtained by the E771 experiment conducted at Fermilab. No evidence is found. A 90% confidence level upper limit of 4.2×10^{-6} is obtained for the branching ratio. This new upper limit is about two times lower than the best published result. [S0031-9007(96)01183-0]

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One of the outstanding symmetries of the standard model (SM) is approximate flavor conservation in electroweak neutral current interactions. Historically, the charm quark was proposed to account for the highly suppressed decay rate of the strangeness nonconserving neutral current process $K_L \to \mu^+\mu^-$ [1]; the charm quark completes a two-generation quark model which forbids $K_L \to \mu^+\mu^-$ at the lowest (tree) level. The observed branching ratio (BR) of $(7.4 \pm 0.4) \times 10^{-9}$ [2] is consistent with higher order electroweak processes, involving insertion of loops to the tree-level diagrams [3]. Recently, the beauty changing neutral current process $B \to K^*\gamma$ has been observed at a rate expected from the three-generation SM [4].

The down-type quarks (d, s, and b) contribute to the loop diagrams in the charm changing neutral current process $D^0 \to \mu^+\mu^-$, resulting in a rate proportional to m_s^4, where m_s is the mass of the strange quark [3]. The expected BR at the quark level (short distance) for $D^0 \to \mu^+\mu^-$ is about 10^{-19} [5], about 14 orders of magnitude below the present experimental limit [2]. Nonperturbative quantum chromodynamics (long distance) effects may enhance the BR by several orders of magnitude [5], but still render the SM decay rate undetectable by current or future experiments. Consequently, this decay mode offers a clean search window for models with flavor changing neutral currents (FCNCs) at the tree level [6]. For such models, $D^0 \to \mu^+\mu^-$ is predicted to have a BR of 10^{-9}

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5.10 E781/SELEX - STUDY OF CHARM BARYON PHYSICS

Bogazici (Turkey), Bristol (United Kingdom), Carnegie-Mellon, CBPF (Brazil), Fermilab, Hawaii, IHEP/Beijing (China), IHEP/Protvino (Russia), Iowa, ITEP (Russia), Moscow State (Russia), MPI/Heidelberg (Germany), Paraiba (Brazil), PNPI (Russia), Rochester, INFN/Rome (Italy), Rome (Italy), San Luis Potosi (Mexico), Sao Paulo (Brazil), Tel Aviv (Israel), INFN/Trieste (Italy), Trieste (Italy)

E781/SELEX was a successor to the charged hyperon experiments E715 and E761. The collaboration was built on the charge hyperon collaboration from these experiments plus parts of E653 charm collaboration. E781/SELEX extended the definition of hyperon a bit to include strange baryons which also have charm quarks. The connection is two fold, since we've used the 600 GeV/c hyperon beam (half Σ^- !) to produce the charm particles, hoping to enhance the number of strange-charmed states. The detector was a state of the art spectrometer with a high precision micro-vertex detector and first class particle ID from a photo-tube based Ring Imaging Cherenkov counter and TRDs to detect charm states with lifetimes as short as 1/25 of a B meson (~60 fsec).

The strange-charmed baryons Ξ_c^+(csu), Ξ_c^0(csd) and Ω_c^0(css) are, even today, relatively unexplored territory. There are only 750 events in the Particle Data Book for all modes of all three states, in all experiments. E781/SELEX will help to change this with larger samples of cleaner events. Our initial charmed baryon paper is the first observation of a Cabibbo suppressed decay mode $\Xi_c^+ \rightarrow pK^-\pi^+$ with a total of 260 events in 3 modes. We will measure the lifetimes of all 7 weakly decaying charmed particles along with many of their production and decay properties. There is also a broad program of non-charmed physics in E781/SELEX ranging from measurements of the total scattering cross section and electro-magnetic radius of the Σ^- thru searches for various exotica like pentaquark states.

E781 Degree Recipients

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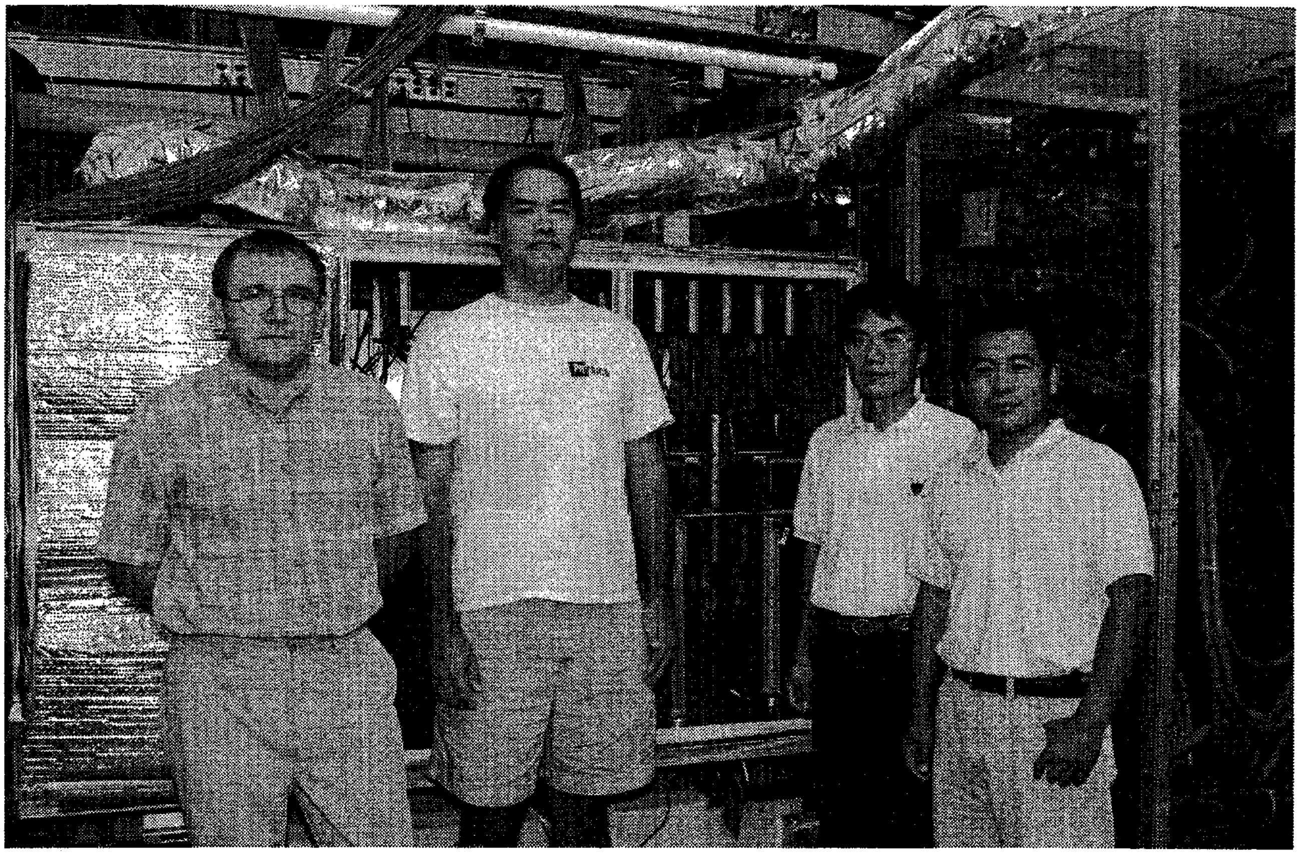

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Observation of the Cabibbo suppressed decay $\Xi_c^+ \rightarrow pK^-\pi^+$., S.Y. Jun, *et al.*, Phys. Rev. Lett. **84**,1857 (2000).
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Observation of the Cabibbo-Suppressed Decay $\Xi_c^+ \to pK^-\pi^+$

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We report the first observation of the Cabibbo-suppressed charm baryon decay $\Xi_c^+ \to pK^-\pi^+$. We observe $150 \pm 22 \pm 5$ events for the signal. The data were accumulated using the SELEX spectrometer during the 1996–1997 fixed target run at Fermilab, chiefly from a 600 GeV/c Σ^- beam. The branching fractions of the decay relative to the Cabibbo-favored $\Xi_c^+ \to \Sigma^+K^-\pi^+$ and $\Xi_c^+ \to \Xi^-\pi^+\pi^+$ are measured to be $B(\Xi_c^+ \to pK^-\pi^+)/B(\Xi_c^+ \to \Sigma^+K^-\pi^+) = 0.22 \pm 0.06 \pm 0.03$ and $B(\Xi_c^+ \to pK^-\pi^+)/B(\Xi_c^+ \to \Xi^-\pi^+\pi^+) = 0.20 \pm 0.04 \pm 0.02$, respectively.

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The study of Cabibbo-suppressed (CS) charm decays can provide useful insights into the weak interaction mechanism for nonleptonic decays [1]. The observed final state may arise either from direct quark emission at the decay stage or, in some cases, from quark rearrangement due to final-state scattering. By comparing the strengths of CS decays to their Cabibbo-favored (CF) analogs, one can, in a systematic way, assess the contributions of the various mechanisms.

Modern methods for calculating nonleptonic decay rates of the charm hadrons employ heavy quark effective theory and the factorization approximation [2]. Nonetheless, the

5.11 E789 - BEAUTY-QUARK MESONS AND BARYONS

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E789 was designed to study two-body, two-prong decays of neutral hadrons that contain a charm quark or a bottom quark. E789 was an exploratory effort that failed to achieve sufficient sensitivity to see two-prong B-quark decays due to their very small decay fraction. Nevertheless, E789 did measure J/ψ decays from B mesons, two-body charm decay modes, and also provided new information on the cross sections and nuclear effects of D^o production in 800 GeV/c proton-nucleus collisions. These results were compared to QCD predictions.

E789 also measured the yield of J/ψ mesons from nuclear targets. The J/ψ yield per target nucleon is observed to decrease for heavy nuclei. This effect, similar to what is predicted for J/ψ production in very high-energy nucleus-nucleus quark-gluon plasma formation interactions, is not yet understood.

E789 Degree Recipients

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C. Lee	M.S.	Northern Illinois University
V. Martin	M.S.	Northern Illinois University
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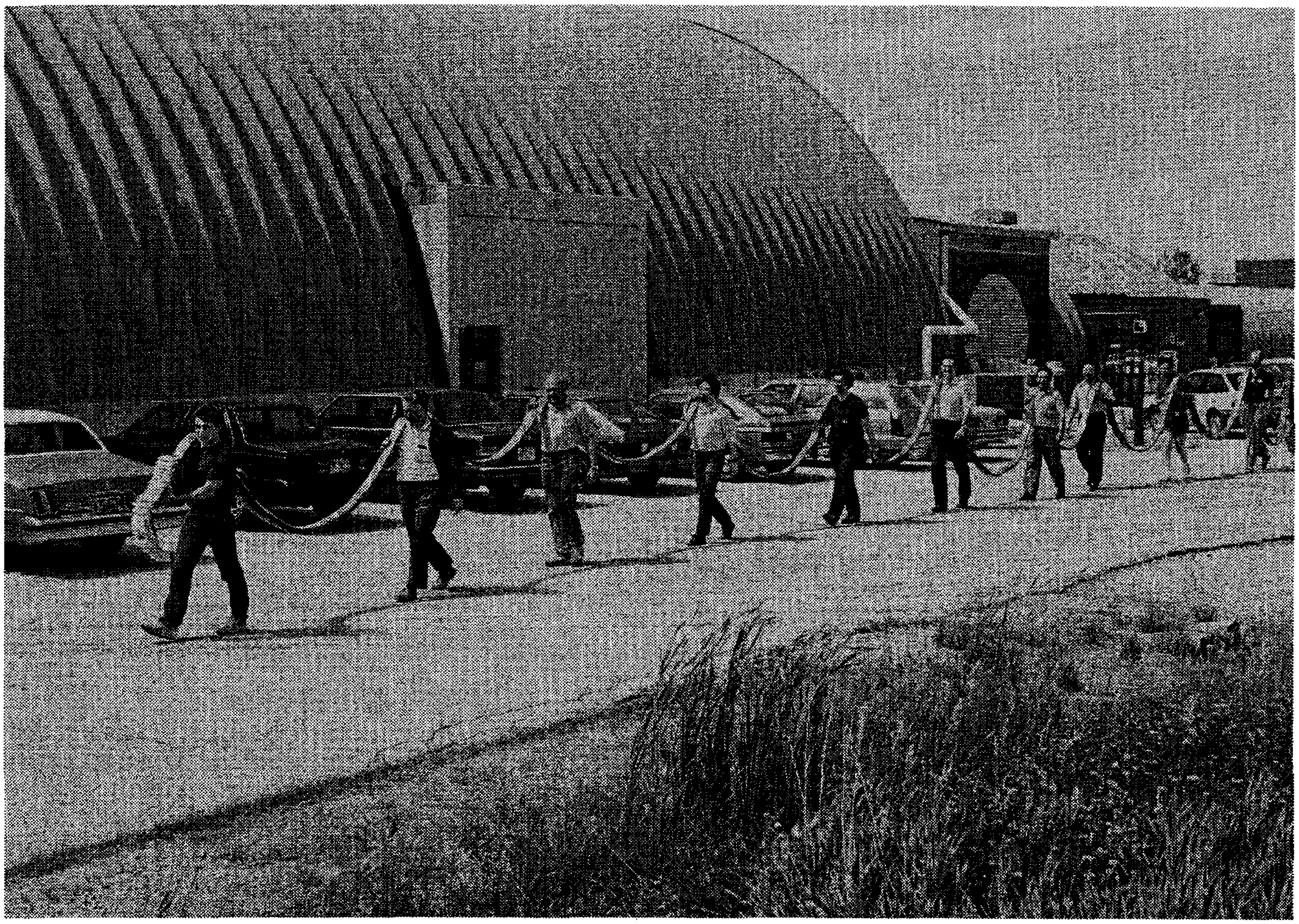

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Measurement of the Bottom-Quark Production Cross Section in 800 GeV/c Proton-Gold Collisions

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Using a silicon-microstrip detector array to identify secondary vertices, we have observed $b \to J/\psi \to \mu^+\mu^-$ decays in 800 GeV/c proton-gold interactions. The doubly differential cross section for J/ψ mesons originating from b-quark decays, assuming linear dependence on nucleon number, is $d^2\sigma/dx_F\,dp_T^2 = 107 \pm 28 \pm 19$ [pb/(GeV/c)^2]/nucleon at $x_F = 0.05$ and $p_T = 1$ GeV/c. This measurement is compared to next-to-leading-order QCD predictions. The integrated b-quark production cross section, obtained by extrapolation over all x_F and p_T, is $\sigma(pN \to b\bar{b} + X) = 5.7 \pm 1.5 \pm 1.3$ nb/nucleon.

PACS numbers: 13.85.Ni, 25.38.Qk, 24.85.+p, 25.40.Ve

We report the first measurement of the b-quark production cross section in proton-nucleus interactions. Production of b quarks was observed via inclusive $b \to J/\psi \to \mu^+\mu^-$ decays. Previous measurements of the b-quark production cross section are available from the CERN [1] and Fermilab [2–4] $p\bar{p}$ colliders, and from fixed-target experiments using pion beams [5]. These data have been compared to recent next-to-leading-order calculations for b-quark production [6]. Our measurement provides proton-induced data, at a smaller $\sqrt{s}$ than the colliders, which can be used to test the QCD predictions.

The experiment was performed at Fermilab using the E605 spectrometer [7]. The spectrometer can detect pairs of charged particles, has good mass resolution, and can handle high interaction rates. To provide sufficient resolution in vertex position to distinguish the decays of b hadrons from the copious "prompt" (i.e., originating at the primary interaction vertex) backgrounds, we added an array of 16 silicon-microstrip detectors (SMDs) downstream of the target. We also increased the data-acquisition capacity by an order of magnitude (to 50 Mbytes/spill) and replaced the multiwire proportional chambers with small-cell drift chambers.

An 800 GeV/c primary proton beam was incident along the z axis upon a rectangular gold target 5 cm $\times$ 0.2 mm $\times$ 3 mm ($\Delta x \times \Delta y \times \Delta z$) in size, where the target center defined the origin of the coordinate system and the y axis was in the vertical direction. Because of the wirelike shape of the target, the primary interaction vertex had well-localized y and z coordinates which need not be reconstructed. The high laboratory momenta ($\approx$150 GeV/c) of b hadrons within our acceptance imply that the production and decay vertices are separated by an average distance of 1.3 cm. Vacuum extended from far upstream of the target to a 130-μm-thick titanium window located 28 cm downstream of the target, ensuring that interactions in windows or in air could not be confused with b-hadron decays.

The SMDs were 5 cm $\times$ 5 cm $\times$ 300 μm single-sided detectors with a 50-μm strip pitch. They were situated 37 to 94 cm downstream of the target, in an enclosure filled with helium gas cooled to 10 °C, and grouped into an upper and a lower arm. Each arm consisted of four y-view detectors with strips lying horizontally and four stereo-view detectors with strips tilted $\pm 5°$ from the x axis. The angular coverage of the instrumented strips, $20 \le |\theta_y| \le 60$ mr, matched the acceptance of the magnetic spectrometer. Signals from 8544 strips were processed by Fermilab-Penn preamplifiers [8] and LBL discriminators [9] followed by latches. The resolution in decay distance provided by the SMD arrays, $\approx$0.7 mm rms, was confirmed by reconstructing the decays of D^0 mesons produced in 800 GeV/c proton-nucleus interactions [10]. The close agreement of the D^0 lifetime obtained there with the world average [11] further confirms our understanding of the SMD calibration and efficiency.

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5.12 E791 - HADROPRODUCTION OF CHARM

E-791: UC/Santa Cruz, CBPF (Brazil), Cincinnati, CINVESTAV (Mexico), Fermilab, IIT, Kansas State, Mississippi, Ohio State, Princeton, Puebla (Mexico), Rio de Janeiro (Brazil), Stanford, South Carolina, Tel Aviv (Israel), Tufts, Wisconsin, Yale

The primary goal of the E791 experiment was to obtain detailed information on as large a number as possible of interactions in which charm quarks were produced. The information was to be used to study a range of physics issues from the way quarks turn into every-day particles to searches for phenomena not explained by known entities and interactions, "physics beyond the standard model" as it is called. These studies involved both the production characteristics and decay properties of charm particles.

E791 has published 8 papers on charm production and 16 on charm decays. Notably, these include the best current limits on several physics processes beyond the standard model: Flavor Changing Neutral Currents and other rare and forbidden decays, charm particle-antiparticle mixing, and CP violation in charm decays. Measurements of parameters of the standard model were also made, including particle lifetimes, several charm decay branching ratios, and form factors. From the details of the charm particle decays to multiple particles, E791 has contributed to the understanding of the dynamics of charm particle decay as well as measuring the parameters of several poorly-known particles which appear in charm decay. Another first was the search for a five-quark state, the pentaquark, which is expected in the standard model but has never been observed. E791 publications include papers on the total and differential production rates for charm particles and on particle-antiparticle production asymmetries.

E791 was the last in the series of experiments at the Fermilab Tagged Photon Laboratory (TPL). The final three in the series of four experiments took advantage of the Tevatron accelerator. In addition, E791 extended the philosophy of the earlier experiments in using "triggers" minimally - essentially recording almost every hadronic interaction event to magnetic tape. However, E791 used the expanded capabilities of parallelism in data collection, recording, and analysis computing made possible by more recent technologies. These technologies included 8 mm video tape used to record digital data, greatly expanded numbers of commercial computers to collect and organize data in real time, expanded banks of memory made possible by much less expensive storage, and "farms" of off-line computing engines working in parallel on processing data. In addition, E791 used a target for the incident beam which provided space for the produced charm particles to decay in air between target foils. Having the decays observed outside of material led to clear signals, unencumbered by backgrounds due to interactions in the target material. These approaches succeeded spectacularly, in that E791 recorded 50 terabytes of data containing the information on 20 billion interactions (a world record at the time) and successfully reconstructed about 250,000 charm events from this sample.

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E791 Publications

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Lifetimes and lifetime difference between $D^0 \rightarrow KK$ and $D^0 \rightarrow K\ \pi$., E.M. Aitala, *et al.*, Phys. Rev. Lett. **83**, 32 (1999).
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Search for $D^0\overline{D}^0$ Mixing in Semileptonic Decay Modes

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(Received 20 May 1996)

We report the result of a search for $D^0\overline{D}^0$ mixing in the data from hadroproduction experiment E791 at Fermilab. We use the charge of the pion from the strong decay $D^{*+} \to D^0\pi^+$ (and charge conjugate) to identify the charm quantum number of the neutral D at production, and the charge of the lepton and the kaon in the semileptonic decays $D^0 \to Ke\nu$ and $K\mu\nu$ to identify the charm at the time of decay. No evidence of mixing is seen. We set a 90% confidence level upper limit on mixing of $r < 0.50\%$, where $r = \Gamma(D^0 \to \overline{D}^0 \to K^+l^-\overline{\nu}_l)/\Gamma(D^0 \to K^-l^+\nu_l)$. [S0031-9007(96)01122-2]

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The predicted rate of $D^0\overline{D}^0$ mixing in the standard model [1] is several orders of magnitude below the sensitivity of current experiments. However, several theoretical extensions to the Standard Model (e.g., theories with a heavy fourth-generation quark with $-1/3$ charge, scalar leptoquark bosons, or flavor-changing neutral Higgs bosons) predict $D^0\overline{D}^0$ mixing rates high enough to be measurable by existing experiments, making it interesting to search for this process [2]. The mixing rate is parametrized as $r = \Gamma(D^0 \to \overline{D}^0 \to \overline{f})/\Gamma(D^0 \to f)$, where f is the final decay state used to identify the charm quantum number of the neutral D at the time of decay. We report here a limit on r using semileptonic decays in the data from Fermilab experiment E791.

Many experiments have used hadronic D^0 decays to search for mixing. For example, Fermilab experiment E691 studied $D^0\overline{D}^0$ mixing by looking for the decay chain $D^{*+} \to \pi^+D^0$, followed by $D^0 \to \overline{D}^0 \to K^+\pi^-$ or $K^+\pi^-\pi^+\pi^-$ [3]. A wrong-sign charged K from the neutral D decay (e.g., $D^0 \to \overline{D}^0 \to K^+\pi^-$) can be a signature of mixing. However, a wrong-sign K can also come from doubly-Cabibbo-suppressed (DCS) decays in which a D^0 decays directly into the wrong-sign kaon (e.g., $D^0 \to K^+\pi^-$). Moreover, the DCS amplitude can interfere with the mixing amplitude, reducing the

5.13 E831/FOCUS - HEAVY QUARKS STUDY USING THE WIDEBAND PHOTON BEAM

UC/Davis, CBPF (Brazil), CINVESTAV (Mexico), Colorado, Fermilab, INFN/Frascati (Italy), Illinois/Champaign, Korea (Korea), INFN/Milano (Italy), Milano (Italy), North Carolina, INFN/Pavia (Italy), Pavia (Italy), Puebla (Mexico), Puerto Rico/Mayaguez, South Carolina, Tennessee, Vanderbilt, Wisconsin, Yeonsei (Korea)

FOCUS is a high intensity photoproduction experiment that is designed to study the production and decay of charmed particles. The experiment enjoyed a successful data-taking period during 1996 and 1997 and reconstructed more than 1 million charm particles in D^o, $D^+ \rightarrow K\pi$, $K\pi\pi$, and $K\pi\pi\pi$.

Several improvements were made in the spectrometer upgraded from E687. A scintillating fiber calorimeter was fabricated and implemented in the first level trigger to improve efficiency. Both the first and second level triggers were speeded up in order to increase the livetime and silicon strip detectors were interleaved with the BeO segmented target. New detectors both reduced the electron and muon misidentification as well as improved the electron and muon efficiency.

The physics of the experiment involves high precision studies of D semileptonic decays with an emphasis on the determination of form factors and CKM matrix elements $|V_{cd}|$ and $|V_{cs}|$, QCD studies of double-*D* events, a measurement of the absolute branching fraction for the D^o meson, searches for D^o mixing using hadronic and semileptonic final states, searches for CP violation, rare and forbidden decays, fully leptonic decays of the D^+, and a systematic investigation of charm baryons and their lifetimes.

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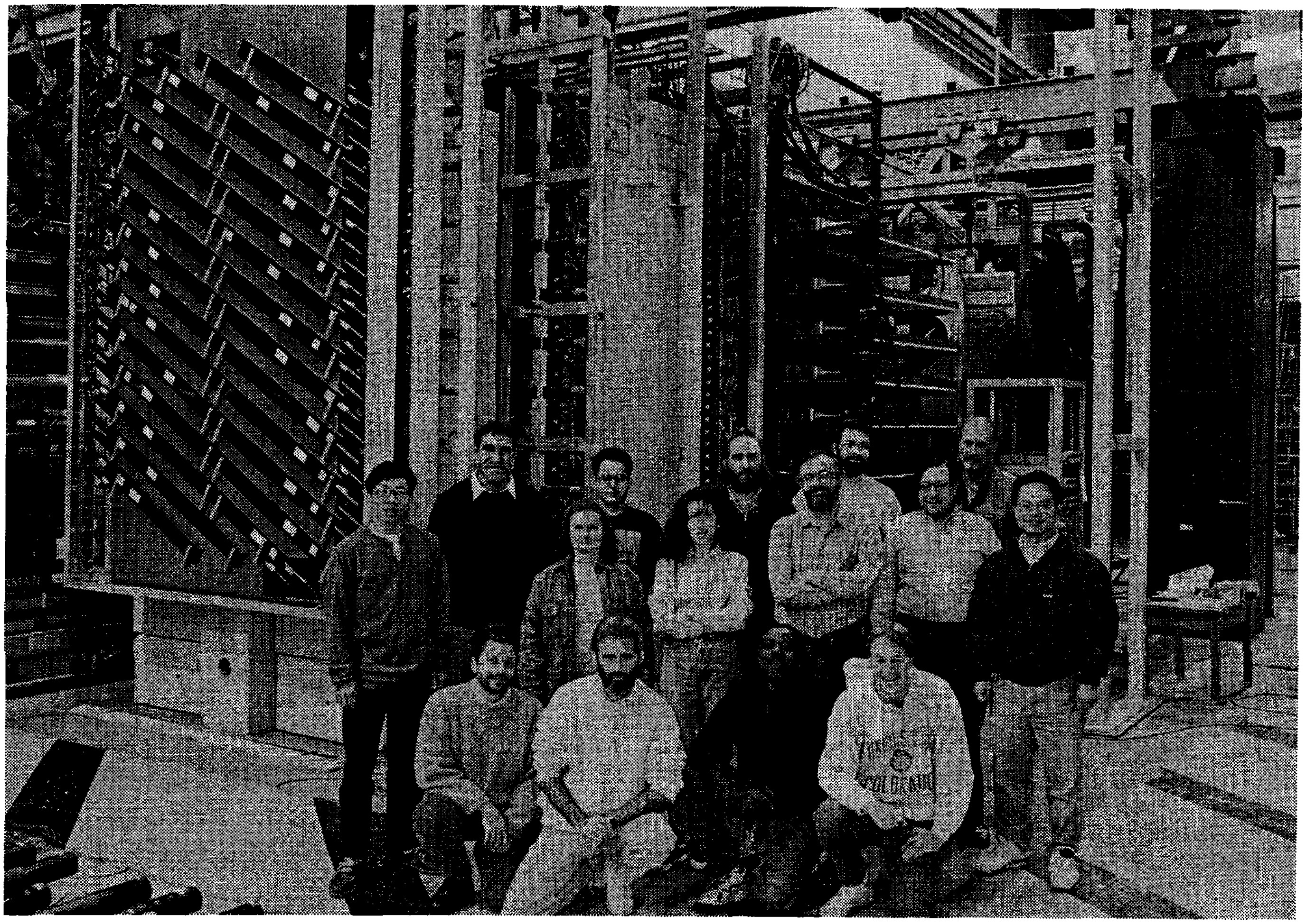

E831 Publications

A Measurement of lifetime differences in the neutral D meson system., submitted to Phys. Lett., [hep-ex/0004034] (Apr 2000) .

A measurement of lifetime differences in the neutral D-meson system

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Abstract

Using a high statistics sample of photoproduced charm particles from the FOCUS experiment at Fermilab, we compare the lifetimes of neutral D mesons decaying via $D^0 \to K^-\pi^+$ and K^-K^+ to measure the lifetime differences between CP even and CP odd final states. These measurements bear on the phenomenology of $D^0 - \bar{D}^0$ mixing. If the $D^0 \to K^-\pi^+$ is an equal mixture of CP even and CP odd eigenstates, we measure $y_{CP} = (\Gamma(\text{CP even}) - \Gamma(\text{CP odd}))/(\Gamma(\text{CP even}) + \Gamma(\text{CP odd})) = 0.0342 \pm 0.0139 \pm 0.0074$.

SYMMETRY TESTS
SECTION 6

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6. SYMMETRY TESTS

6.1 INTRODUCTION

Objects in our everyday macroscopic world are often said to possess symmetry. We say this when there are operations on an object that could alter its appearance, but in fact do not; an example of this is the rotation of a sphere through an angle about its center. Symmetry concepts can be applied not only to the physical processes that govern our local, large scale world, including such things as plant growth, the composition of rocks, and the flight of space ships, but also to the microscopic world.

To fully understand nature's principles, it is believed that studying the relationship between symmetry and the physical laws is best done at the most fundamental level, the level of quarks and leptons. Over the last few decades, the field of elementary particle physics has made tremendous progress in understanding the nature of fundamental interactions and fundamental structure. New discoveries have propelled us toward a substantial strengthening of the Standard Model of particle physics, while advanced technologies have enhanced our ability to investigate the compelling questions of the origins of mass, matter and antimatter in the universe, and the basic nature of symmetry. Symmetry arguments have a long and extensive history, including the history of many of the basic principles of physical laws. And, with the introduction of successful quantum field theories and more mathematically rigorous techniques over the decades, symmetry principles have been used as tools to help define and extend natural laws. Also, experimental data has been studied for the accuracy of compliance with symmetry principles; and when symmetry is violated, to what degree and by what mechanisms.

The experiments that operated during the Tevatron fixed target era extended the investigation of the relatively old symmetry in nature known as CP, including the search and study of extremely rare decay processes. The C in this mathematical formulation represents the independent symmetry that describes the interchange of matter and antimatter. The P in this combined operation represents the independent symmetry of parity, an operation that changes left to right (like looking in a mirror). The combined operation, CP, was thought to be invariant in particle interactions, i.e., the interactions would be symmetrical in CP terms. However, in some very rare cases, this symmetry is violated. The masses and interactions of particles are nearly identical to those of their corresponding antiparticles, but there is a small difference in this CP symmetry of nature, only observed so far in the decays of K mesons. Since matter and antimatter mutually annihilate, and (at creation) our universe is postulated to include equal amounts of matter and antimatter, this very small CP difference may contribute a crucial bit of information that helps explain the abundance of matter over antimatter in the universe today. Although an ongoing program, differences in the accuracy of the experimental measurements of these processes world wide has provided another motivation for new studies. A number of experiments presented here had a goal, not of just observing this well established symmetry violation, but to measure the parameters of these very rare processes to high precision. The results could improve our understanding of these phenomena in the context of the Standard Model, which so successfully describes many aspects of elementary particle interactions.

These experiments also provided some of the most versatile detector instruments built during this era, making it possible also to study hyperon physics, to make particle lifetime measurements, and to search for supersymmetric particles. Forethought in the design of the beams, particularly in the kaon experiments, also provided for the creation of exceptional, secondary, neutral hyperon beams that allowed dedicated studies of hyperons produced at high energies. The scope of these studies also includes the search for violation of well established symmetries such as CPT, where one includes the operation of time reversal invariance T and searches for rare, short lived new particles. The results gained from the successful study of CP violation in the decay of the neutral kaon, does not answer one intriguing question; why is this symmetry violation seen only in the kaon system? Many non-kaon experiments around the world are currently underway to search for this symmetry violation in other systems. Experiments are underway on CP violation in hyperon decay at Fermilab and on B meson decay here and at other laboratories – with high priority.

The Fermilab fixed target symmetry experiments produced a number of high precision, rare decay measurements, including first measurements of some decay modes. One such measurement observed the first CP violating effect in an angular distribution variable, and included demonstrated CP- and T-odd effects in the asymmetry. From the successful early measurements of CP violating symmetries to unprecedented precision, to the latest fixed target experiments and the results of further analysis to follow, these experiments are well on their way to completing their goals.

6.2 E621 - MEASUERMENT OF CP VIOLATION PARAMETER η_{+-0}

Michigan, Minnesota, Rutgers

This experiment measured the CP violation parameter η_{+-0} by measuring the interference between K_s^0 and K_L^0 decays to $\pi^+ \pi^- \pi^0$ near a kaon production target. The experiment was performed in the "neutral hyperon beam" previously used for E619. The measured interference is dependent on both the proper lifetime of the kaon and the exact acceptance versus decay distance of the spectrometer. By using two different target distances from the spectrometer, the acceptance systematics were minimized and the lifetime of the K_s was measured to 0.5% accuracy. The lifetime measurement allowed a stringent test of any possible momentum dependence of the kaon lifetime as had been predicted for a "fifth force".

E621 Degree Recipients

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E621 Degree Recipients

New Measurement of the amplitude of the CP conserving decay $K_S^{\vee} \rightarrow \pi^{\prime} \pi\ \pi^{\vee}$., Y. Zou, *et al.*, Phys. Lett. **B369**, 362 (1996).
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Measurement of the Lifetime of $\Xi^{\vee} \rightarrow \Sigma^{\vee}\gamma$ *Mesons in the Momentum Range 100 to 350 GeV/c.*, S. Tiege, *et al.*, Phys. Rev. Lett., **63**, 2717 (1989).
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Measurement of the Lifetime of K_S^0 Mesons in the Momentum Range 100 to 350 GeV/c

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(Received 13 February 1987)

In an experiment at Fermilab we have measured the lifetime of K_S^0 mesons produced by 800-GeV/c protons on tungsten. $K_S^0 \to \pi^+\pi^-$ decays from 100 to 350 GeV/c, between 9.3 and 25.3 m from production, were selected for the measurement. The result was $(0.8920 \pm 0.0044) \times 10^{-10}$ sec, in excellent agreement with measurements performed for 2–5-GeV/c K_S^0. The lifetime was also calculated for seven momentum bins. The results were completely consistent with Lorentz invariance. No evidence was found for the momentum dependence suggested by the intermediate-range "fifth-force" hypothesis.

PACS numbers: 13.25.+m, 14.40.Aq

In this Letter we report high-precision measurements of the K_S^0 lifetime (τ_S) made over a wide range of kaon momenta. While it is intrinsically important to measure the basic parameters of the K^0-$\bar{K}^0$ system, our τ_S measurement was also motivated by recent speculation[1] about the existence of a fifth force that couples to hypercharge. The data were collected during Fermilab experiment 621 to search for CP-symmetry nonconservation in $K_S^0 \to \pi^+\pi^-\pi^0$ decays.

In a reanalysis of three K_S^0 regeneration experiments at Fermilab, Aronson, Bock, Chen, and Fischbach[2] (ABCF) found evidence that the values of four K^0-$\bar{K}^0$ parameters changed with the kaon's momentum over the range 30–110 GeV/c. These were Δm, the mass difference of $K_L^0 - K_S^0$; $|\eta_{+-}|$, the magnitude of the CP-nonconservation parameter in $K_L^0 \to \pi^+\pi^-$ decay; ϕ_{+-}, the phase of η_{+-}; and τ_S. In these experiments a K_L^0 beam strikes a target, and the number of $\pi^+\pi^-$ decays in the forward direction, per unit proper time t, dN_R/dt, is

$$\frac{dN_R}{dt} = B_{+-}\frac{N_L}{\tau_S}\left\{|\rho|^2\exp\left(\frac{-t}{\tau_S}\right) + |\eta_{+-}|^2\exp\left(\frac{-t}{\tau_L}\right) + 2|\rho|\,|\eta_{+-}|\cos(\Delta m\,t + \phi_\rho - \phi_{+-})\exp\left[-\frac{t}{2}\left(\frac{1}{\tau_S}+\frac{1}{\tau_L}\right)\right]\right\}, \quad (1)$$

where B_{+-} is the $K_S^0 \to \pi^+\pi^-$ branching ratio, N_L is the number of K_L^0 in the beam, τ_L is the K_L^0 lifetime, and ρ is the (complex) regeneration amplitude with phase ϕ_ρ. These experiments were designed to measure ρ (and extract the difference of K^0 and $\bar{K}^0$ forward scattering amplitudes), not to measure K^0-$\bar{K}^0$ decay parameters. As ABCF point out, with so many parameters affecting proper time dependence, it is not easy to isolate the effect of any one parameter by fitting Eq. (1) to regeneration data.

We avoid this problem in our experiment by studying decays of K_S^0 made in proton-tungsten collisions, rather than by regeneration, and by choosing a proper time range where the contribution of CP nonconservation is insignificant. A proton beam of momentum 800 GeV/c struck a tungsten target, 9.6 cm long and 3.5 mm in diameter, located at the entrance to the Fermilab Proton Center Hyperon Magnet, which is 7.3 m long, weighs 400 tons, and has a 3.5-T field. A collimator was located in the magnet with a defining aperture 3.2 mm in diameter 4.0 m from the target. It allowed only neutral particles to pass through the magnet and enter our detector, a pair spectrometer. Figure 1 shows the target, magnet, collimator, and detector. Two 1-mm-thick scintillation counters V1 and S1, located inside an evacuated pipe, defined a decay region between 8.1 and 26.7 m from the target. Six multiwire proportional chambers (MWPC's), and an analysis magnet with transverse momentum bend of 1.6 GeV/c were used to reconstruct

6.3 E731 - A PRECISION MEASUREMENT OF THE CP VIOLATION PARAMETER (ε'/ε) IN THE NEUTRAL KAON SYSTEM

Chicago, Elmhurst, Fermilab, Princeton, Saclay (France)

The E731 proposal was to build a new beam and detector for the sole purpose of measuring ε'/ε. Indeed no other physics was mentioned in the proposal, which had only seven authors. The 1983 proposal goal was a measurement to a precision of 0.001; the final result was $(7.4 \pm 5.9) \times 10^{-4}$, not far enough from zero to claim an effect but enough, together with the CERN result at the time, to launch a new generation of measurements: see the write-up on E832 for the latest results and a fuller description of the motivation behind this measurement. This E731 result remained the highest precision result until quite recently.

The experiment took advantage of the higher energy kaons that could be made with the Tevatron, and of the much superior duty cycle of the machine. In addition, the detector designed solely for the purpose of clean $\pi\pi$ reconstruction could make unexpectedly significant measurements in other channels, particularly multi-body modes including gammas and/or electrons. The facility of measuring other channels was due to the high precision and excellent background rejection with which the high-energy secondaries could be reconstructed. It was also in E731 that the advantages for high sensitivity rare kaon decay physics at a high energy machine became apparent. These advantages lead to the proposal and execution of E799I and E799II. The KAMI initiative with the Main Injector, now under development, is also a direct result of this experience.

Many decay channels were studied in E731. The highlights included: the first limit on the $\pi^0 e^+ e^-$ decay mode rate, the first limit on the π^0 ν anti-ν decay mode rate, a high statistics study of the K_{e4} mode, and unique observations on the $\pi\pi\gamma$ final state, including the observation of the interference between the K_L and K_S decays. The first two of these decay channels are likely to have large CP violating components.

E731 Degree Recipients

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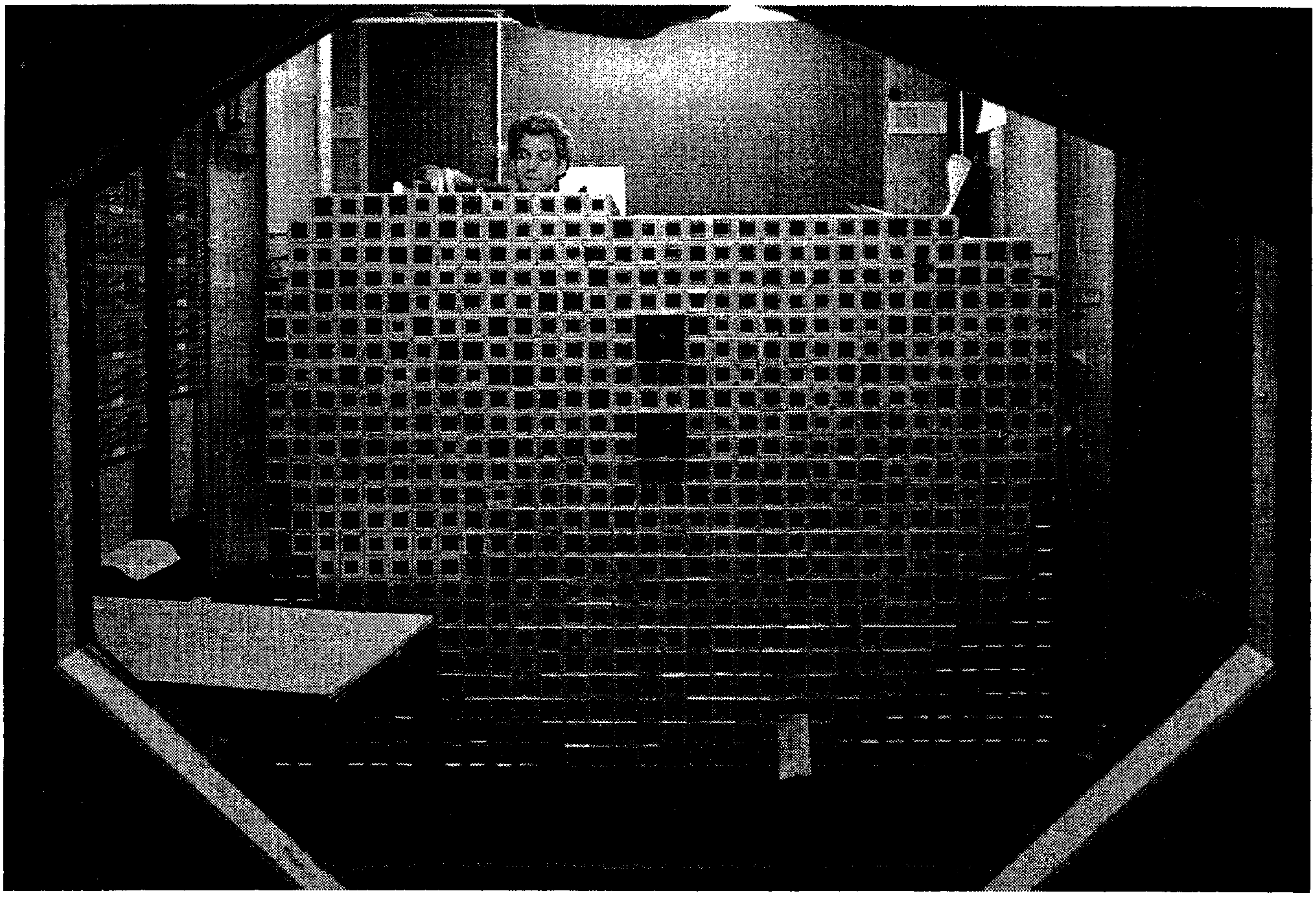

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Measurement of the *CP*-Violation Parameter $\mathrm{Re}(\varepsilon'/\varepsilon)$

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A measurement of the *CP*-violation parameter $\mathrm{Re}(\varepsilon'/\varepsilon)$ has been made using the full E731 data set. We find $\mathrm{Re}(\varepsilon'/\varepsilon)=(7.4\pm5.2\pm2.9)\times10^{-4}$ where the first error is statistical and the second systematic.

PACS numbers: 13.25.+m, 11.30.Er, 14.40.Aq

Since the discovery [1] of *CP* violation in K_L decays in 1964, all manifestations of *CP* violation have been consistent with time-asymmetric oscillations (parametrized by ε) between particle and antiparticle, in this case the neutral kaon. The standard Cabbibo-Kobayashi-Maskawa (CKM) model [2] can naturally accommodate *CP* violation but it also predicts direct *CP* violation (DCPV), wherein a particle of one *CP* eigenstate can decay directly to a final state of opposite *CP*. There are alternative theories, such as the "superweak" [3] model, so it is important to refine searches for DCPV. While strong evidence [4] for DCPV in 2π decays of the neutral kaon was given in 1988, our collaboration gave a result [5] in 1990 based upon a 20% data set consistent with no DCPV. The result from the entire data set is presented in this paper [6], including a complete reanalysis of the earlier sample. This new result uses an enlarged fiducial region for the $K_L\to2\pi$ decays. Extensive improvements in the understanding of the detector allow a factor of 2 reduction in the systematic error.

The presence of DCPV, parametrized by ε', would shift the ratio of *CP*-violating to *CP*-conserving $\pi\pi$ decay amplitudes, η, of the charged relative to the neutral final state. Thus the following double ratio of rates would differ from unity:

$$\frac{|\eta_{+-}^2|}{|\eta_{00}^2|}=\frac{|\varepsilon+\varepsilon'|^2}{|\varepsilon-2\varepsilon'|^2}=\frac{\Gamma(K_L\to\pi^+\pi^-)/\Gamma(K_S\to\pi^+\pi^-)}{\Gamma(K_L\to\pi^0\pi^0)/\Gamma(K_S\to\pi^0\pi^0)}\approx1+6\,\mathrm{Re}(\varepsilon'/\varepsilon)\,.$$

In the CKM model, the expected [7] level for $\mathrm{Re}(\varepsilon'/\varepsilon)$ is of order 0.001.

To minimize systematics, K_L and K_S decays to either the neutral or charged final state were collected simultaneously [8]. The experiment used two parallel kaon beams, one pure K_L and one with K_S produced by coherent regeneration. Producing K_S this way gives K_L and K_S beams with identical spatial and similar momentum distributions. Because the decays from the two beams are collected simultaneously, the ratio of rates in the two beams is largely insensitive to accidental activity and to changes in detector or accelerator performance on any time scale during the run. However, the difference in the K_S and K_L lifetimes requires that the detector acceptance as a function of decay vertex be well understood. Many K_L decays to the $\pi e\nu$ ($Ke3$) and $3\pi^0$ final states were collected to aid in the acceptance determination.

Detailed descriptions of the detector and of reconstruction techniques can be found in the preceding paper [9] and other publications [5,10–12]. We give the essentials here. To reconstruct the $\pi^+\pi^-$ decays, tracks measured with a drift chamber spectrometer were used to determine the $\pi^+\pi^-$ momenta, mass, and decay vertex. For $\pi^0\pi^0$ decays, the energies and positions of the four photons were measured with an 804 block lead glass calorimeter. The best pairing of photons into two pions gave the kaon decay position and the $\pi^0\pi^0$ mass. A trigger plane, including a 0.5 mm Pb sheet in the first 60% of the $\pi^0\pi^0$ data, was located near the center of our neutral fiducial volume. It is important that the event trigger, reconstruction, and selection criteria were *independent* of the beam from which the kaon decayed.

6.4 E773 - MEASUREMENT OF THE PHASE DIFFERENCE BETWEEN η_{00} AND η_{+-} TO A PRECISION OF 1°

Chicago, Elmhurst, Fermilab, Illinois, Rutgers

Quantum field theories of the fundamental interactions require that particles and antiparticles have identical masses and lifetimes. It is, however, conceivable that violations of this exact matter-antimatter symmetry could occur at the miniscule distance scales associated with the violent disruptions of space and time caused by quantum gravitational effects. The very small mass difference between long- and short-lived K mesons (K_L and K_S) provides a possible experimental tool for detecting these effects. Experiment 773 was designed to study the interference between decaying K_L and K_S mesons in a neutral particle beam at Fermilab in order to search for signs of this *CPT violation.*

The experiment determined the relative phases between quantum mechanical amplitudes characterizing decays of K mesons into pairs of charged and neutral pions. The ratio of the amplitudes for $K_L \rightarrow \pi^+ \pi^-$ and $K_S \rightarrow \pi^+ \pi^-$ decays (η_{+-}) is expected to be nearly identical to the corresponding ratio for $K_L \rightarrow \pi^0 \pi^0$ and $K_S \rightarrow \pi^0 \pi^0$ (η_{00}). In particular, a difference in the phases of the amplitudes η_{+-} and η_{00} that was larger than a fraction of a degree would be an indication that the masses of K mesons and anti-K mesons differ. E773 found that this difference in phases was (0.63±1.03) degrees, consistent with CPT conservation. When combined with results from E731, this corresponds to a mass difference between K^0 and the K^0 antiparticle that is less than roughly 1 part in 10^{18} of the K^0 mass. This precision would correspond to weighing Lake Michigan with an experimental error equal to one teaspoon of water. The E773 result was one of the measurements listed in the American Physical Society's *Physics News in 1995.*

E773 Degree Recipients

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E773 Publications

CPT tests in the neutral kaon system., B. Schwingenheuer, *et al.*, Phys. Rev. Lett. **74**, 4376 (1995).
New measurement of the CP violation parameter $\eta_{+-\gamma}$, J.N. Matthews, *et al.*, Phys. Rev. Lett. **75**, 2803 (1995).

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CPT Tests in the Neutral Kaon System

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Fermilab experiment E773 has measured the phases $\Phi_{+-} = 43.53^\circ \pm 0.97^\circ$ and $\Phi_{00} - \Phi_{+-} = 0.62^\circ \pm 1.03^\circ$ of the *CP* violating parameters η_{+-} and η_{00} from interference in the decay of neutral kaons into two charged or neutral pions from a pair of regenerators. New measurements of the K_L-K_S mass difference and the K_S lifetime are also given. These results test *CPT* symmetry and show no evidence for a violation.

PACS numbers: 11.30.Er, 13.25.Es, 14.40.Aq

CPT symmetry in particle physics follows from very general assumptions [1]; nevertheless, continued experimental tests are warranted. While *C*, *P*, and *CP* symmetry violations are established, no violation of *CPT* has been reported. The neutral kaon system has provided very stringent tests of *CPT*; the two most precise of these are presented in this Letter.

CP violation is parametrized by the measurable ratios of decay amplitudes:

$$\eta_{+-} = \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)} = |\eta_{+-}|e^{i\Phi_{+-}}, \quad (1)$$

with a similar expression for η_{00} in $\pi^0\pi^0$ decays. If *CPT* is not violated, one can show [2] that

$$\Delta\Phi = \Phi_{00} - \Phi_{+-} \approx 0. \quad (2)$$

In addition, excluding unexpectedly large *CP* violation in decays other than $\pi\pi$, it also follows that [2]

$$\Phi_{+-} \approx \Phi_{SW} \equiv \arctan\frac{2\Delta m}{\Delta\Gamma}, \quad (3)$$

where $\Delta m = m_L - m_S$ and $\Delta\Gamma = \Gamma_S - \Gamma_L$ are the mass and decay width differences of K_L and K_S.

In Fermilab experiment E773, two K_L beams struck two different regenerators. Downstream of its regenerator, each beam is a coherent superposition $|K_L\rangle + \rho|K_S\rangle$. Here, ρ is the forward regeneration amplitude, which depends on the kaon momentum and the composition of the regenerator. The decay rate into two pions is

$$R(t) \propto |\rho e^{-it(m_S - i\Gamma_S/2)} + \eta e^{-it(m_L - i\Gamma_L/2)}|^2, \quad (4)$$

where t is the proper time of the decay relative to the end of the regenerator. By measuring the decay rates into both neutral and charged pions, the phases $\Phi_\rho - \Phi_{+-}$ and $\Delta\Phi$ can be extracted from the interference terms. In addition, one can determine Δm and $\tau_S = 1/\Gamma_S$ (Γ_L is sufficiently well known). The regeneration amplitude ρ is proportional to $(f - \bar{f})/k$, the difference of the nuclear scattering amplitudes. In our energy range, $|(f - \bar{f})/k|$ follows, to a good approximation, a power law in the kaon momentum $p = \hbar k$, and its phase is determined though a dispersion relation $(f - \bar{f})/k \propto p^{\alpha-1}\exp[-i\pi(1 + \alpha)/2]$. Elsewhere [3] the uncertainty in the extraction of the phase Φ_ρ of the regeneration amplitude from its momentum dependence is treated. This Letter, then, reports on both tests (2) and (3) of *CPT* symmetry.

E773 took data for three months in the 1991 fixed-target run at Fermilab. The apparatus (Fig. 1) was essentially the same as for the 1987–88 run (experiment E731 [4]) and is described in more detail elsewhere [5]. The two K_L beams were produced by 800 GeV protons striking a beryllium target. The detector components were located between 115 and 190 m downstream of the target. The regenerators, which were made of plastic scintillator

 0031-9007/95/74(29)/4376(4)$06.00

6.5 E774 - ELECTRON BEAM DUMP PARTICLE SEARCH

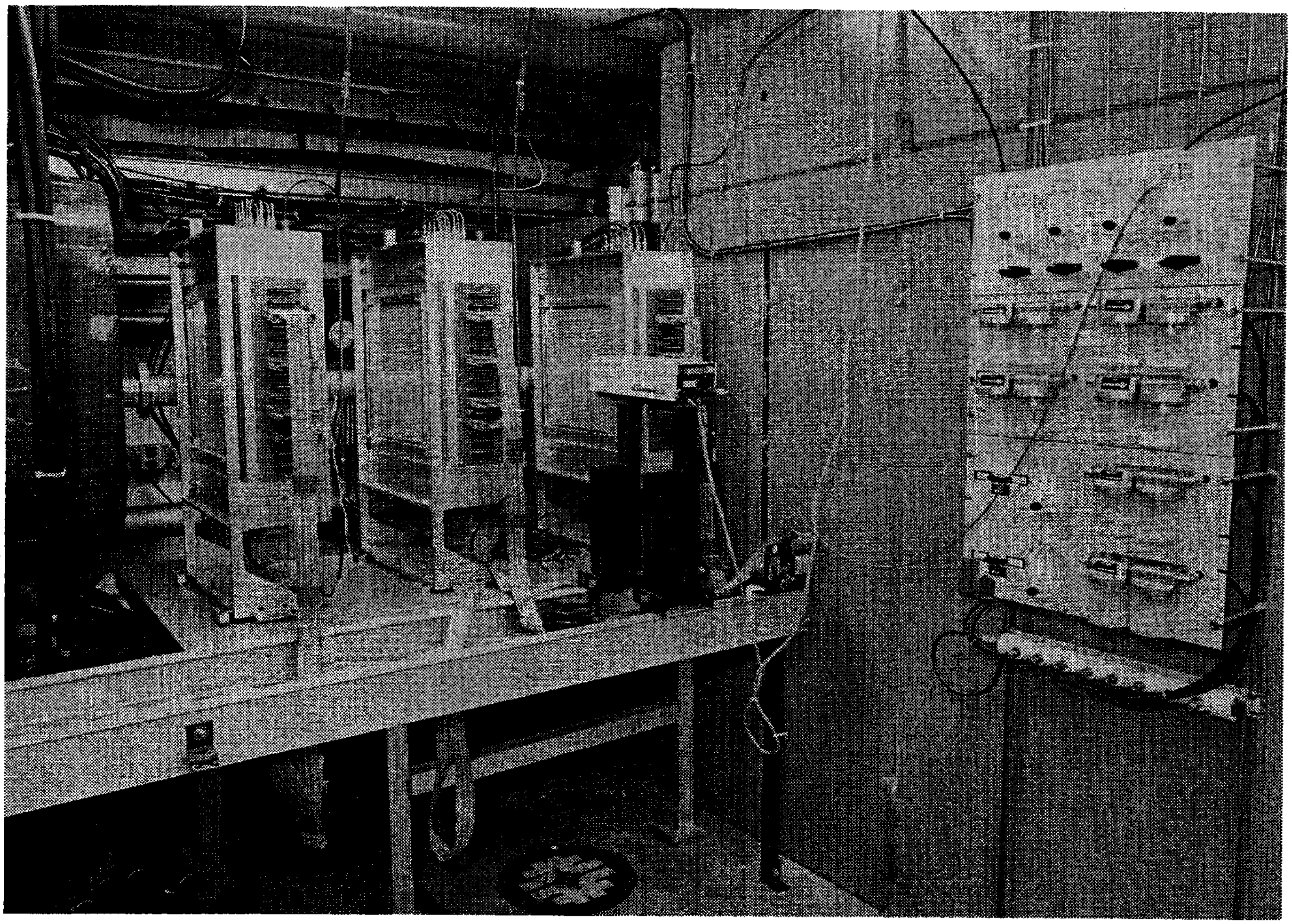
Fermilab, Illinois, Northeastern

In the early 1980's, experiments at the GSI heavy ion accelerator in Darmstadt observed a striking anomaly in the production of electrons and positrons in elastic collisions of heavy ions. The anomalous signal consisted of coincident electron-positron pairs having approximately equal energies *in the laboratory frame,* and was interpreted as evidence for the two-body decay of a neutral particle of mass 1.8 MeV/c^2. It was presumed that this new particle was created at rest in the strong electromagnetic fields of the colliding ions. Experimental limits at that time could not exclude such a particle, especially if its coupling was primarily to the electron. Theoretical speculation was that this could be a variant of the axion.

E-774 was one of many electron beam dump experiments mounted around the world to search for this object. The technique was simple. A beam of high energy electrons was directed into a dense beam absorber. A light neutral particle coupled to the electron would be produced in the beam dump by a bremsstrahlung-like process and could then be observed by its decay in flight if its flight path were longer than the beam dump. E-774 was unique in that it used the Wide Band electron beam at Fermilab which at nearly 400 GeV was the highest energy electron beam in the world. This gave the best sensitivity to short lifetimes.

The beam dump for E-774 was a dense tungsten calorimeter, 60 radiation lengths deep and instrumented with scintillating fiber ribbons. The calorimeter was thick enough to completely absorb the high-energy electron showers so that a veto counter at its downstream face could operate quietly and define the beginning of the decay volume. The entire assembly of beam dump calorimeter plus veto counters was about 25 cm long, allowing sensitivity to lifetimes below 10^{-15} sec. Following the decay volume, an array of scintillation counters and a downstream electromagnetic calorimeter were used to trigger on decays in flight. Track momenta were analyzed using a magnetic spectrometer. Incoming primary beam particles were tagged as electrons using a synchrotron radiation detector. This effectively removed the 10-20% contamination of pions and kaons in the primary beam.

Had the 1.8 MeV/c^2 particle been real, E-774 would have seen a considerable flux of events with a clear and striking signature. A beam electron would hit the beam dump calorimeter but deposit only a fraction of its energy and leave no signal in the veto counter at the beginning of the decay space. The counters at the downstream end of the decay space would register two charged particles. The beam energy missing from the beam dump calorimeter would appear in the downstream trigger calorimeter, and this energy would match the momenta of the electron-positron pair reconstructed in the momentum spectrometer. E-774 took data during the 1987-88 and 1990 fixed target runs. While a considerable flux of electron-positron pairs was seen from neutral kaon decays, all of these events were excluded by kinematics and/or by the tagging of the primary beam. No events were found which were consistent with the two-body decay hypothesis, and the experiment was able to exclude the last remaining lifetime region for the 1.8 MeV/c^2 object.



E774 Publications

Search for Short-lived Particles Produced in an Electron Beam Dump., A. Bross, *et al.*, Phys. Rev. Lett. **67**, 2942 (1991).

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Search for Short-Lived Particles Produced in an Electron Beam Dump

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(Received 12 July 1991)

A search for short-lived neutral particles which decay to electron-positron pairs has been carried out using a beam of 275-GeV electrons incident on an instrumented tungsten beam dump. The experiment was sensitive to particles up to 10 MeV/c^2 in mass and down to 4×10^{-16} sec in lifetime.

PACS numbers: 14.80.Gt, 13.60.Hb

Monoenergetic positron peaks seen in heavy-ion collision experiments [1] at the Gesellschaft für Schwerionenforschung (GSI) have been interpreted as a signal for the production and subsequent decay into an electron-positron pair of a new neutral boson X_0 with mass about 1.8 MeV/c^2 [2]. This suggestion was supported by the observation of coincident electron-positron pairs having equal laboratory energies ($E_{e^+}+E_{e^-}=1.8$ MeV/c^2 $-2m_e$) [3]. Although simple models for a neutral X_0 are constrained by limits obtained from precision atomic physics experiments [4,5] and by null results from previous searches in nuclear decay [6], in beam-dump experiments [7–9] and in low-energy Bhabha scattering [10], the GSI data have focused attention on a region of mass and lifetime where short-lived neutral bosons could exist and yet would not have been observed.

More recently, the production of e^+e^- pairs by heavy ions in emulsion has been presented [11,12] as evidence for new neutral bosons with masses less than 10 MeV/c^2 and lifetimes between 3×10^{-16} and 1.5×10^{-15} sec.

In this Letter, we report results from a new electron beam-dump experiment, Fermilab E-774. In an electron beam dump, a neutral X_0 will be produced by a process analogous to bremsstrahlung [13]; it can then be detected by its decay in flight into an e^+e^- pair provided it does not decay or interact inside the beam dump. If the X_0 decays predominantly into e^+e^-, its production rate is determined by a single coupling constant which is in turn fixed by the presumed mass and lifetime of the X_0.

The experiment used an electron beam with 275-GeV/c mean momentum, $\pm6\%$ momentum spread, and 6% hadron contamination. The apparatus (Fig. 1) included a set of beam-defining scintillation counters, a tungsten electromagnetic calorimeter (the electron beam dump), and a pair of scintillation counters immediately behind the dump to veto events in which any charged particles emerged. A second calorimeter with separate electromagnetic and hadronic sections was located 7.25 m downstream from the beam dump. Between the beam dump and the downstream calorimeter, all particles passed through four scintillation counters. The pulse heights recorded in these counters were used to determine the charge multiplicity of neutral particles decaying in flight. The first of these counters was 2 m downstream from the beam dump and defined the end of the decay space for charged final states. Near the end of the decay space, an additional veto counter with a 5-cm-square hole was used to tag events with wide angle tracks.

Because the bremsstrahlung production spectrum of a particle of mass $>2m_e$ is strongly peaked at high secondary energy and small production angle [13], a new particle would cause an excess of events with large energy deposition in the downstream electromagnetic calorimeter, signals corresponding to two charged particles in the decay volume scintillators, and no wide angle tracks.

The experiment trigger required an energy deposition

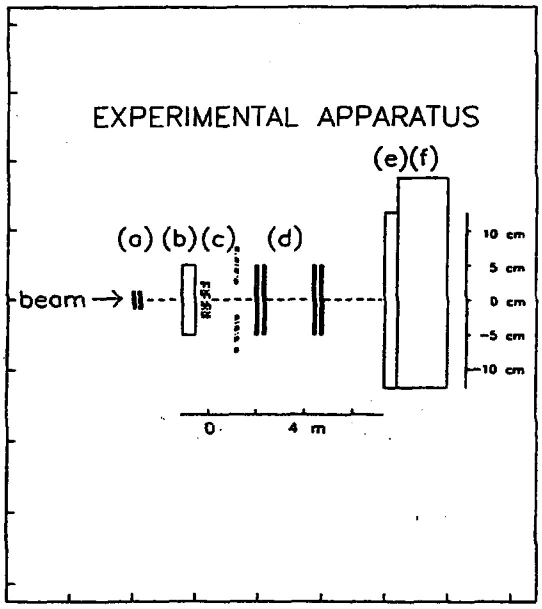


FIG. 1. Layout of experimental apparatus showing (a) beam counters, (b) target calorimeter, (c) veto counters, (d) multiplicity counters, (e) trigger electromagnetic calorimeter, and (f) hadron calorimeter.

6.6 E799 RARE DECAYS OF K_L^0 AND HYPERONS

Arizona, UCLA, UC/San Diego, Campinas (Brazil), Chicago, Colorado, Elmhurst, Fermilab, Osaka (Japan), Rice, Rutgers, Sao Paulo (Brazil), Virginia, Wisconsin

The high intensity and high energy protons provided by the Tevatron, allowed a major extension of the experimental sensitivity to rare, neutral kaon decays. E799 took advantage of this new opportunity. The sensitivity of the experiment crucially depended on both the number of observed kaon decays (flux and acceptance) and resolution of the detector. The combination of Tevatron and the E799-Phase I detector provided these ingredients.

E799-I published results on a search for the breakdown of the fundamental symmetry of charge-conjugation-parity (CP), which could manifest itself in rare kaon decay processes that include a pion and a pair of leptons. Additional results included tests of the principles of unitarity, lepton-number conservation, hyperon polarization, and kaon form factors. All of these results were the best at the time, and held the record for many years. This experiment also set the stage for the rare kaon decays in the years beyond 2000, especially on the most important "Golden Mode" K_{Long} decay to a neutral pion with two neutrinos. This very rare kaon decay mode provides the cleanest measurement of the CP violating parameter η of the Standard Model. E799-Phase I was a pioneering experiment that proved the viability of research on many key physics questions that are best answered by rare kaon decays.

Besides the importance of the physics of this whole series of experiments, perhaps an unconventional 'parameterization' of these small scale, sharply-focused experiments is the educational benefit that can be measured by what students learn and do during their thesis research. Students had to do *everything*; including design the detector, do R&D on various detector elements, construct the detector components, make them all work, do the data-taking, understand in detail the detector performance, and finally do the physics analysis. Six out of the seven E799 – Phase-I PhD students who graduated from this experiment are still practicing the art of experimental physics.

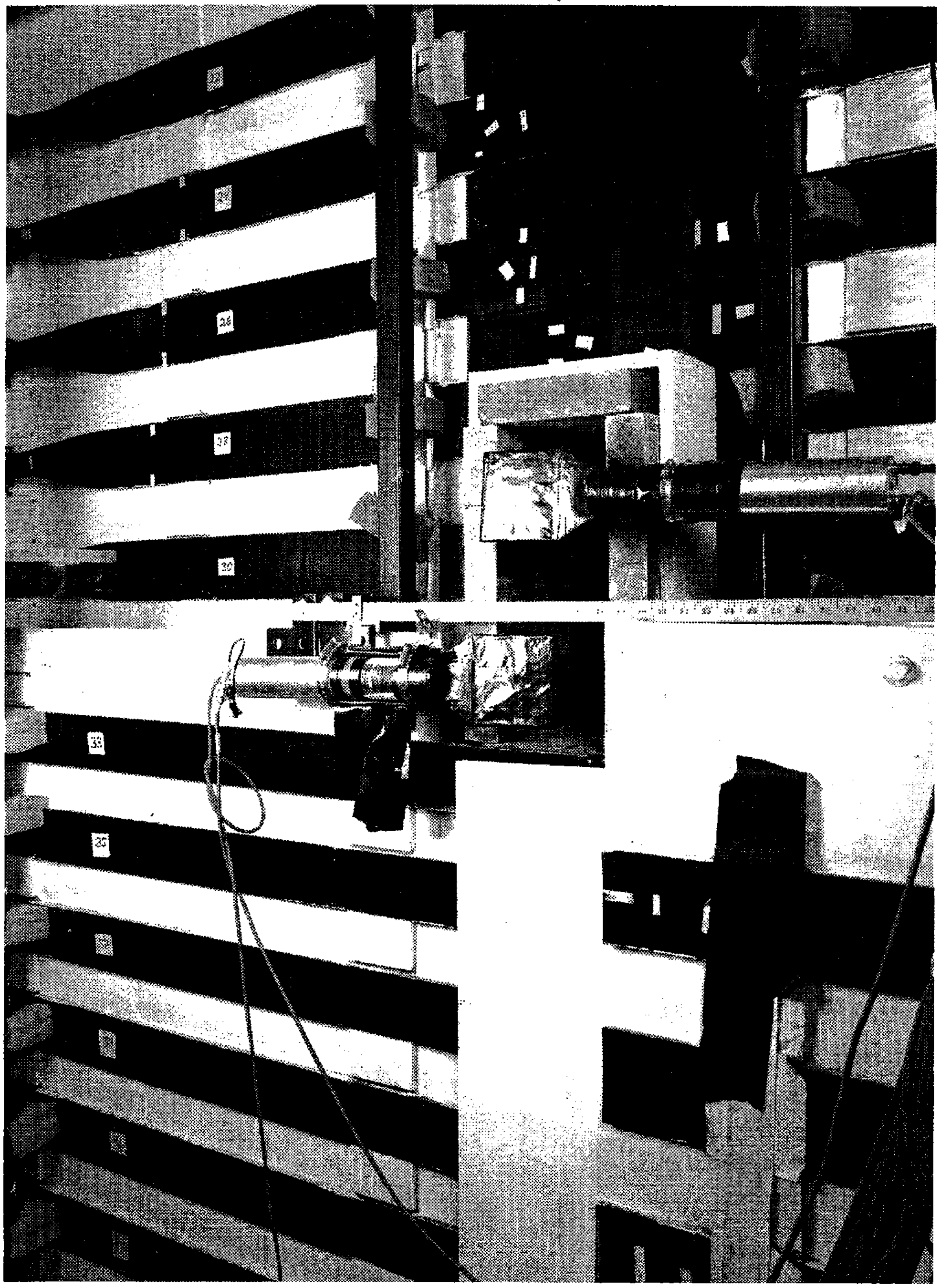
E799 I Degree Recipients

Ping Gu	Ph.D.	Rutgers University
Deborah Appel Harris	Ph.D.	University of Chicago

Fumihiko Kato	M.S.	Osaka University
Kevin Scott McFarland	Ph.D.	University of Chicago
Tsuyoshi Nakaya	Ph.D.	Osaka University
Douglas Alan Roberts	Ph.D.	University of California at Los Angeles
Matthew Brandon Spencer	Ph.D.	University of California at Los Angeles
Matthew John Weaver	Ph.D.	University of California at Los Angeles

E799 I Publications

Measurement of the branching ratio of π^o to e^+e^- from π^o produced by $K_L \rightarrow \pi^o \pi^o \pi^o$ decays in flight., K.S. McFarland, *et al.*, Phys. Rev. Lett. **71**, 31 (1993).
Limit on the branching ratio of $K_L \rightarrow \pi^o \mu^+ \mu^-$., D.A. Harris, *et al.*, Phys. Rev. Lett. **71**, 3914 (1993).
Limit on the branching ratio of $K_L \rightarrow \pi^o e^+ e^-$., D.A. Harris, *et al.*, Phys. Rev. Lett. **71**, 3918 (1993).
A limit on the lepton-family number violating process $\pi^0 \rightarrow \mu$ and e., P. Krolak, *et al.*, Phys. Lett. **B320**, 407 (1994).
Measurement of the branching ratio and a study of CP for the leptonic decay $K_L \rightarrow e^+ e^+ e^- e^-$., P. Gu, *et al.*, Phys. Rev. Lett **72**, 3000 (1994).
Limit on the branching ratio of $K_L \rightarrow \pi^o \nu\ \nu$., M. Weaver, *et al.*, Phys. Rev. Lett.**72**, 3758 (1994).
Search for the decay $K_L \rightarrow \pi^o \pi^o \gamma$, D. Roberts, *et al.*, Phys. Rev. **D50**, 1874 (1994).
Measurement of the branching ratio of $K_L \rightarrow e\ e\gamma\gamma$, T. Nakaya, *et al.*, Phys. Rev. Lett **73**, 2169 (1994).
Polarization of Λ and anti-Λ produced by 800 Gev protons., E.J. Ramberg, *et al.*, Phys. Lett. **B338**, 403 (1994).
Measurement of the branching ratio and form factor of $K_L \rightarrow \mu\ \mu\ \gamma$, M.B. Spencer, *et al.*, Phys. Rev. Lett **74**, 3323 (1995).
First evidence for the decay $K_L \rightarrow \mu\ \mu\ e\ e$., P. Gu, *et al.*, Phys. Rev. Lett **76**, 4312 (1996).
Search for the lepton-family number violating decays $K_L \rightarrow \pi^o \mu\ e$., K. Arisaka, *et al.*, Phys. Lett. **B432**, 230 (1998).



Following the first run of E799, a new spectrometer and beam line were developed for the combined E799 Phase II and the ε'/ε experiment E832. This combination is referred to as KTeV. Good pion/electron discrimination was achieved, over 10,000 to 1, by the combination of a precision CsI calorimeter and a transition radiation detector. These capabilities greatly improved the sensitivity of the experiment.

KTeV-E799 addressed the principles of unitarity and lepton-number conservation, the polarization of hyperons, and kaon form factors. A particular kaon decay, K_L to a pair of charged pions and a electron-positron pair, was observed to manifest CP and T violations in a decay angle asymmetry. This is the first observation of a CP-odd and T-odd variable in physics, and provides guidance towards understanding symmetry breaking. The experimenters are still in the early phase of analyzing data collected during 1996/97 and 1999, and expect to publish (essentially rewrite the chapters on neutral kaon decays with) many results in future years.

E799 II Degree Recipients

A. Alavi-Harati	Ph.D.	University of Wisconsin
Steve Bright	Ph.D.	University of Chicago
G. Graham	Ph.D.	University of Chicago
K. Hanagaki	Ph.D.	Osaka University
Kazunori Hanagaki	M.S.	Osaka University
Satoshi Hidaka	M.S.	Osaka University
Yuji Matsumiya	M.S.	Osaka University
P. Mikelsons	Ph.D.	University of Colorado
B. Quinn	Ph.D.	University of Chicago
M. Sadamoto	Ph.D.	Osaka University
Masayoshi Sadamoto	M.S.	Osaka University
K. Senyo	Ph.D.	Osaka University
Masanori Sogo	M.S.	Osaka University
Toshihiro Tsuji	M.S.	Osaka University
Motoharu Yagi	M.S.	Osaka University
Eric Zimmerman	Ph.D.	University of Chicago

E799 II Publications

Measurement of the branching fraction of the decay $K_L \to \pi^+ \pi^- e^+ e^-$., A. Alavi-Harati, *et al.*, Phys. Rev. Lett. **80**, 4123 (1998).
Search for the decay $K_L \to \pi^0 \nu \nu$., A. Alavi-Harati, *et al.*, Phys.Lett. **B447**, 240 (1999).
Observation of $\Xi^0 \to \Sigma^+ e^- \nu$., A. Affolder, *et al.*, Phys. Rev. Lett. **82**, 3751 (1999).
Measurement of the decay $K_L \to \pi^0 \gamma \gamma$., A. Alavi-Harati, *et al.*, Phys.Rev.Lett. **83**, 917 (1999).
Measurement of the branching ratio of $K_L \to \pi^0 e^+ e^-$ using $K_L \to 3\pi^0$ decays in flight., A. Alavi-Harati, *et al.*, Phys. Rev.Lett. **83**, 922 (1999).
Observation of CP Violation in $K_L \to \pi^+ \pi^- e^+ e^-$., A. Alavi-Harati, *et al.*, Phys. Rev. Lett. **84**, 408 (2000).
Search for the Weak Decay of a Lightly Bound H^0 Dibaryon., A. Alavi-Harati, *et al.*, Phys. Rev. Lett. **84**, 2593 (2000).
Search for the decay $K_L \to \pi^0 \nu \nu$ using $\pi^0 \to e^+ e^- \gamma$., A. Alavi-Harati, *et al.*, Phys.Rev. **D61**, 2006 (2000).
Search for the Decay $K_L \to \pi^0 \mu^+ \mu^-$., A. Alavi-Harati, *et al.*, to be published in Phys. Rev. Lett.
Observation of the Decay $K_L \to \mu^+ \mu^- \gamma \gamma$., A. Alavi-Harati, *et al.*, Submitted to Phys.Rev. **D**.

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Observation of CP Violation in $K_L \to \pi^+\pi^-e^+e^-$ Decays

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(KTeV Collaboration)

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(Received 2 August 1999)

We report the first observation of a manifestly CP violating effect in the $K_L \to \pi^+\pi^-e^+e^-$ decay mode. A large asymmetry was observed in the distribution of these decays in the CP-odd and T-odd angle ϕ between the decay planes of the e^+e^- and $\pi^+\pi^-$ pairs in the K_L center of mass system. After acceptance corrections, the overall asymmetry is found to be [13.6 ± 2.5(stat) ± 1.2(syst)]%. This is the largest CP-violating effect yet observed when integrating over the entire phase space of a mode and the first such effect observed in an angular variable.

PACS numbers: 11.30.Er, 13.20.Eb

The KTeV E799 experiment at Fermi National Accelerator Laboratory recently reported the first observation [1] of the four body decay mode $K_L \to \pi^+\pi^-e^+e^-$. Based on 2% of the data, a branching ratio of 3.2 ± 0.6(stat) ± 0.4(syst) $\times 10^{-7}$ was measured. In this paper, we report an analysis of the entire KTeV E799 data from which the $K_L \to \pi^+\pi^-e^+e^-$ signal (shown in Fig. 1) of 1811 events above background was obtained after the analysis cuts described below. We observed in these $K_L \to \pi^+\pi^-e^+e^-$ data a CP-violating asymmetry in the CP- and T-odd variable $\sin\phi\cos\phi$,

$$A = \frac{N_{\sin\phi\cos\phi>0.0} - N_{\sin\phi\cos\phi<0.0}}{N_{\sin\phi\cos\phi>0.0} + N_{\sin\phi\cos\phi<0.0}}, \qquad (1)$$

where ϕ is the angle between the e^+e^- and $\pi^+\pi^-$ planes in the K_L center of mass system (cms). This asymmetry implies, with the mild assumption of unitarity to avoid exotic CPT violation [2], time reversal symmetry violation. The quantity $\sin\phi\cos\phi$ is given by $(\hat{n}_{ee} \times \hat{n}_{\pi\pi}) \cdot \hat{z}(\hat{n}_{ee} \cdot \hat{n}_{\pi\pi})$, where the $\hat{n}$'s are the unit normals and $\hat{z}$ is the unit vector in the direction of the $\pi\pi$ in the K_L cms.

The observed asymmetry $\sin\phi\cos\phi$ shown in Fig. 2 was [23.3 ± 2.3(stat)]% before corrections. Inspection of Fig. 2 shows that the asymmetry between the bins near $\sin\phi\cos\phi = \pm 0.5$ is considerably larger. As discussed below, this cannot be explained by asymmetries due to either the spectrometer acceptance or detector elements. Using the model of Refs. [3–5] to correct for regions of $K_L \to \pi^+\pi^-e^+e^-$ phase space outside the acceptance of the KTeV spectrometer (which have small asymmetry), an asymmetry integrated over the entire phase space of the $K_L \to \pi^+\pi^-e^+e^-$ mode of [13.6 ± 2.5(stat)]% was obtained, the largest such CP- (and T-) violating effect yet observed. In comparison, CPLEAR recently reported a [0.66 ± 0.13(stat)]% T-violating asymmetry [6] between $K^0 \to \overline{K}^0$ and $\overline{K}^0 \to K^0$ transition rates.

The $K_L \to \pi^+\pi^-e^+e^-$ data were accumulated during the ten weeks of E799 operation. A proton beam with intensity in the range (3.0–3.5) $\times 10^{12}$ protons per 23 sec spill incident at an angle of 4.8 mr on a BeO target was employed to produce two nearly parallel

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6.7 E832/KTEV A SEARCH FOR DIRECT CP VIOLATION IN $K_L^0 \rightarrow 2\pi$

Arizona, UCLA, UC/San Diego, Campinas (Brazil), Chicago, Colorado, Elmhurst, Fermilab, Osaka (Japan), Rice, Rutgers, Sao Paulo (Brazil), Virginia, Wisconsin

One of the long-lasting puzzles in particle physics is the origin of the CP violation, a difference in the behavior of matter and antimatter, where C stands for the charge conjugation (exchange particle and antiparticle) and P stands for the parity (space inversion like mirror image). The CP violation in neutral kaon decays is a tiny effect (about 1 part in 500). Can it be related to the striking asymmetry between matter and antimatter of our universe which appears to be composed entirely of matter, with no astronomical object made of antimatter ever detected? In fact, the only antimatter we find anywhere is the minute quantities produced in high energy particle interactions like the interactions which occur when cosmic rays strike the upper atmosphere and like those studied here at Fermilab.

E832 was one of the two experiments in KTeV (Kaons at the Tevatron), which sought to determine whether or not the effect of CP violation can be fully understood in the context of the present picture of matter (the "Standard Model"). The best way to do this is by making high-precision measurements on decays that are known to manifest CP violation. This requires large numbers of clean long-lived neutral kaons (K_{Long}), each of which is a mixture of matter particle kaon (K^0) and antimatter particle kaon (anti-K^0). These were produced by the proton beam from Fermilab's Tevatron accelerator. The observed decays came from a long, downstream, vacuum region.

Then fast, precise position and energy measurements were necessary for both electrically charged and neutral particles arising from the decays. The KTeV experiment apparatus thus consisted of a tandem series of state-of-the-art detectors, such as CsI calorimeter, multiwire drift chambers, analyzing magnet, anti-coincidence photon counters, and regenerator (producing side-by-side short-lived kaons). For example, better than 0.7% in precision for the photon energy measurement by the CsI crystal calorimeter has been achieved. Data from the detectors were organized, monitored, displayed, culled, and recorded on magnetic tape by programs running on a powerful 34-processor on-line computer system.

The experiment was constructed beginning in 1992 and took its first data beginning in 1996. E832 took data in 1996,1997 and 1999.

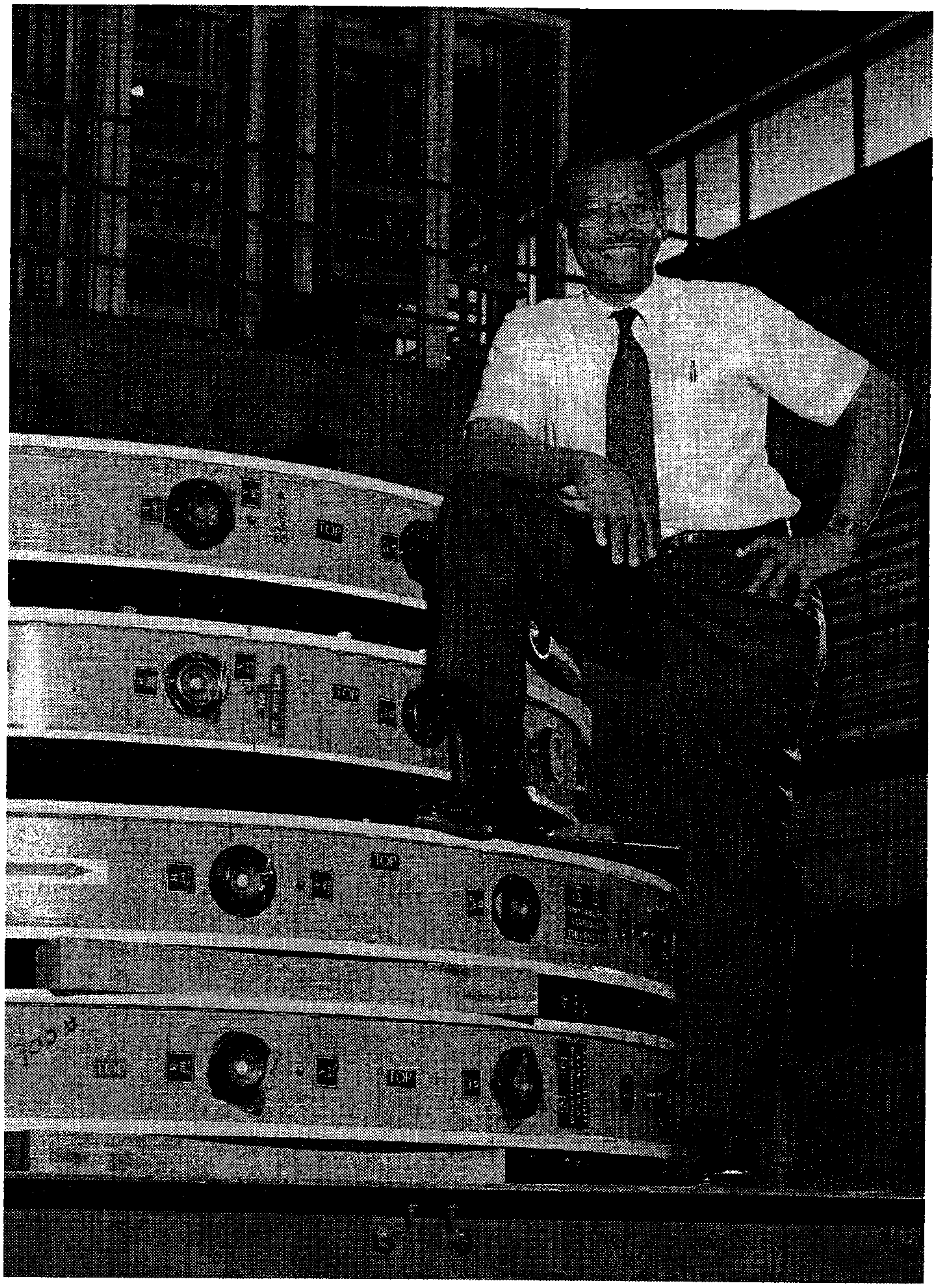
The main purpose of E832 was to measure the quantity ε'/ε (epsilon prime divided by epsilon) which, if non-zero, would signal a new form of CP violation. CP violation was first discovered in the famous experiment of 1964 for which Jim Cronin and Val Fitch received the Nobel Prize. The magnitude of this effect is parameterized by the parameter epsilon, which is about 0.0023. The Cronin-Fitch, or epsilon effect can be described as an asymmetry in the mixing of the neutral kaon with its anti-particle.

Ever since the discovery of the Cronin-Fitch effect, scientists have attempted to observe an effect in the DECAY, rather than the mixing, of the neutral kaon. Such an effect is called "direct" CP violation. The original effect was established by observing the decay of the long-lived neutral kaon to charged pions. To see the new effect, physicists had to study the decay to neutral as well as charged pions, a much more difficult prospect since the neutral pions decay to high energy photons which are difficult to precisely measure. It is necessary to study the decays of the two mixtures of the neutral kaons, called K-long (long-lived) and K-short (short lived), to both the charged and neutral pion final states, which is then parameterized by ε'/ε.

The first KTeV result on ε'/ε was announced in early 1999, based on about 23% of the data already collected from 1996-1997. The analysis was done "blind" up until a week prior to the announcement. The data was sufficiently well understood and the systematic uncertainty was sufficiently small to "open the box" Concluding the preliminary analysis. The result on the ratio ε'/ε is 0.00280 with an error of 0.00041. Thus, the ε' effect is about 350 times smaller than the ε effect. The result serves to establish, with nearly seven standard deviations, this new CP violating effect, direct CP violation. It definitively rules out the Superweak Model as the sole source of CP violation. While the Standard Model predicts a non-zero effect, the size of the KTeV result is larger than most theorists expected.

This result is consistent with the previous finding from a CERN experiment, although their precision (about 3.5 standard deviations) did not lead to definitely reporting a non-zero result. The previous FNAL experiment (see the writeup of E731, this volume) saw a small effect but it was only 1.2 standard deviations from zero.

For the future, it will be interesting to see what results the additional KTeV data sets provide. Some of KTeV's sources of systematic uncertainty have been largely eliminated for its 1999 run and KTeV has doubled the data sample. It will also be interesting to compare new results with CERN and Frascati experiments to further establish the precise measurement of the new CP violating effect. The large amount of data (about 50 Terabytes) collected in E832 was also used to study the decay dynamics of kaons, such as $K_L \rightarrow \pi^+ \pi^- \gamma$ and $\pi^0 \gamma\gamma$, the CP asymmetry in semileptonic K_L decays, as well as searches for supersymmetric particles beyond the Standard Model.



E832 Degree Recipients

Peter S. Shawhan	Ph.D.	University of Chicago

E832 Publications

Light Gluino Search for Decays Containing $\pi^+ \pi^-$ or $\pi^0 \pi^0$ from a Neutral Hadron Beam at Fermilab., A. Alavi-Harati, *et al.*, Phys. Rev. Lett. **83**, 2128-2132 (1999).
Measurement of the Decay $K_L \rightarrow \pi^0 \gamma\gamma$., A. Alavi-Harati, *et al.*, Phys. Rev. Lett. **83**, 917 (1999).
Observation of Direct CP Violation in $K_{LS} \rightarrow \pi\pi$ *Decays.*, A. Alavi-Harati, *et al.*, Phys. Rev. Lett. **83**, 22 (1999).
Search for Light Gluino via the Spontaneous Appearance of $\pi^+ \pi^-$ Pairs with an 800 GeV/c Proton Beam at Fermilab., J. Adams, *et al.*, Phys. Rev. Lett. **79**, 4083 (1997).

VOLUME 83, NUMBER 1 PHYSICAL REVIEW LETTERS 5 JULY 1999

Observation of Direct *CP* Violation in $K_{S,L} \to \pi\pi$ Decays

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We have compared the decay rates of K_L and K_S to $\pi^+\pi^-$ and $\pi^0\pi^0$ final states using a subset of the data from the KTeV experiment (E832) at Fermilab. We find that the direct-*CP*-violation parameter $\mathrm{Re}(\epsilon'/\epsilon)$ is equal to $[28.0 \pm 3.0(\mathrm{stat}) \pm 2.8(\mathrm{syst})] \times 10^{-4}$. This result definitively establishes the existence of *CP* violation in a decay process.

PACS numbers: 13.25.Es, 11.30.Er, 14.40.Aq

The neutral K meson system has been the subject of much study since it was recognized that the two strangeness states (K^0, $\overline{K}^0$) mix to produce short- and long-lived kaons (K_S, K_L). The unexpected discovery of $K_L \to \pi\pi$ decays in 1964 [1] revealed that *CP* (charge-parity) symmetry is violated by the weak interaction, and it was soon understood that the dominant effect is an asymmetry in the K^0-$\overline{K}^0$ mixing, parametrized by ϵ. Ever since, there has been great interest in determining whether *CP* violation also occurs in the $K \to \pi\pi$ decay process itself, an effect referred to as "direct" *CP* violation [2] and parametrized by ϵ'. This would contribute differently to the decay rate for $K_L \to \pi^+\pi^-$ versus $K_L \to \pi^0\pi^0$ (relative to the corresponding K_S decays), and thus would be observable as a nonzero value of

$$\mathrm{Re}(\epsilon'/\epsilon) \approx \frac{1}{6}\left[\frac{\Gamma(K_L \to \pi^+\pi^-)/\Gamma(K_S \to \pi^+\pi^-)}{\Gamma(K_L \to \pi^0\pi^0)/\Gamma(K_S \to \pi^0\pi^0)} - 1\right].$$

The standard Cabibbo-Kobayashi-Maskawa (CKM) model [3] can accommodate *CP* violation in a natural way with a complex phase in the quark mixing matrix. The earliest standard-model calculations of $\mathrm{Re}(\epsilon'/\epsilon)$ [4], which gave values of order $\sim 10^{-3}$–10^{-2}, were done before the top quark mass was known and before the importance of certain diagrams was appreciated. Modern calculations depend sensitively on input parameters and on the method used to estimate the hadronic matrix elements. Most recent estimates have tended toward values near or below 10^{-3}, for example, $(4.6 \pm 3.0) \times 10^{-4}$ [5] and $(8.5 \pm 5.9) \times 10^{-4}$ [6]; however, one group has estimated a larger range of values, $(17^{+14}_{-10}) \times 10^{-4}$ [7]. Alternatively, a "superweak" interaction [8] could produce the observed *CP*-violating mixing but would give $\mathrm{Re}(\epsilon'/\epsilon) = 0$. Therefore, a nonzero value of $\mathrm{Re}(\epsilon'/\epsilon)$

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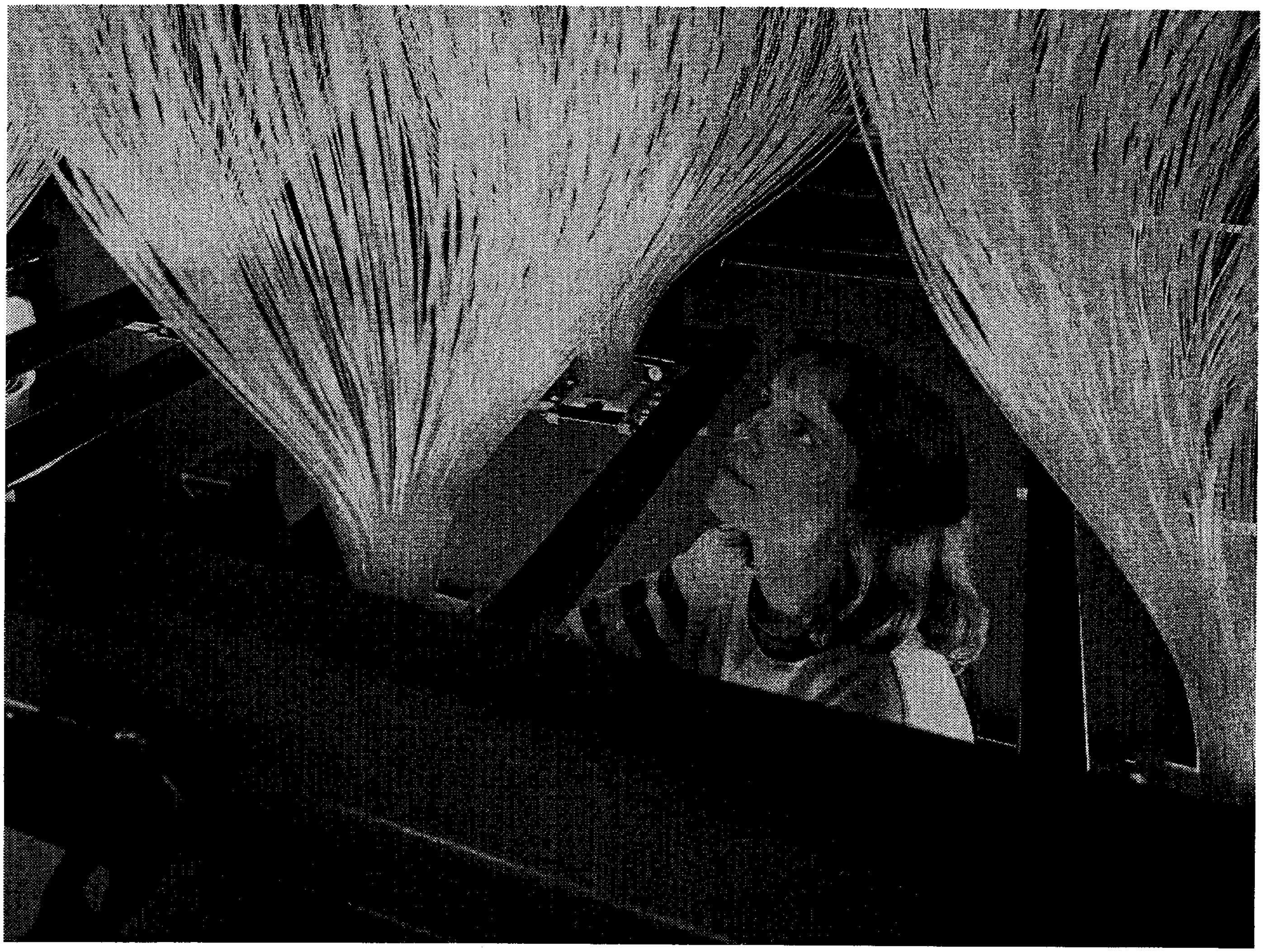
6.8 E871 - SEARCH FOR CP VIOLATION IN THE DECAYS OF $\Xi^- / \bar{\Xi}^+$ AND $\Lambda / \bar{\Lambda}$ HYPERONS

Academia Sinica (Taiwan), UC/Berkeley, Fermilab, Guanajuato (Mexico), IIT, Lausanne (Switzerland), LBNL, Michigan, South Alabama, Virginia

It has been known for over fifty years that antimatter exists. But until 1964, it was thought that, outside of the difference in charge, antimatter should behave identically to matter. That all changed in 1964 when Cronin and Fitch discovered a slight asymmetry between matter and antimatter, or CP violation, in kaon decays. This tiny asymmetry may have cosmological implications. The matter we see now in the universe; stars, planets, dust, people, may all be a consequence of CP violation. This is because in the Big Bang both matter and antimatter should have been created in equal amounts and hence should have mutually annihilated leaving a very boring universe composed of mainly photons. That this didn't happen is thought to be due to CP violation.

Since Cronin and Fitch's discovery, there has been an ever increasing effort to understand CP violation, both experimentally and theoretically. Despite a number of elegant experiments over the past 35 years, it still remains a mystery; and despite some tantalizing evidence from CDF, it still remains a property unique to the decay of the kaons. It should be a universal property of the weak interaction and hence present at some level in (almost) all weak decays. The HyperCP experimenteres are attempting to see CP violation in the decays of two hyperons: the Λ and the Ξ. These are particles much like the proton and neutron except that they contain one or two strange quarks.

Any CP-violation, unlike parity violation, is expected to be small. Hence huge numbers of events are needed. To facilitate this, the HyperCP collaboration built an extremely high-rate spectrometer which recorded more events on tape than any other particle physics experiment: about 75 billion and 160 billion respectively in the 1997 and 1999 fixed-target runs, a total of 100 terabytes of data. In building the spectrometer, the collaboration took advantage of Fermilab's longstanding experience and expertise in hyperon physics and Fermilab's pioneering efforts in very high-rate data acquisition systems. Analysis of the data is still underway and will continue on the Fermilab computing farms for another year. Crunching through 235 billion events takes a while! The collaboration expects to publish some rare and forbidden hyperon decay search results this year, a bit later for the CP violation results.



E871 Degree Recipients

Gennifer Gerbi	Ph.D.	University of Virginia
Durga Ramajaran	Ph.D.	University of Virginia

E871 Conference Proceedings

Status of the HyperCP Experiment at Fermilab., Proceedings of the 3rd International Conference on Hyperons, Charm and Beauty Hadrons, C. Dukes, *et al.*, Nuc. Phys. **75B** ,281 (1999).
Search for Direct CP Violation in Λ and Ξ Hyperon Decays., Proceedings of the 27th International Symposium on Multi-Particle Dynamics, C. White, *et al.*, Nucl. Phys. Proc. Suppl. **71**, 451 (1999).
CP Violation in Strange Baryon Decays: A Report from Fermilab Experiment 871., C. James, et al., Proceedings of the 4th Workshop on Heavy Quarks at Fixed Target (HQ98), Fermilab, October 10, 1998, p.107 (1999).
Search for Direct CP Violation in Decays of Hyperons., Y.C. Chen, *et al.*, Proceedings of the International Conference on Hadron Structure (HS 98), Stara Lesna, Slovakia, September 7, 1998, p.447 (1998).

ELSEVIER Nuclear Physics B (Proc. Suppl.) 75B (1999) 281–287

PROCEEDINGS SUPPLEMENTS

Search for CP Violation in Ξ and Λ Hyperon Decays: Status of the *HyperCP* Experiment

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HyperCP (E871), a Fermilab experiment searching for CP violation in Ξ and Λ hyperon decays, finished its first data taking run at the end of 1997, and accumulated over one billion Ξ^- and $\overline{\Xi}^+$ decays. A sensitivity of approximately 2×10^{-4} in $A_{\Xi\Lambda} = (\alpha_\Xi\alpha_\Lambda - \alpha_{\overline{\Xi}}\alpha_{\overline{\Lambda}})/(\alpha_\Xi\alpha_\Lambda + \alpha_{\overline{\Xi}}\alpha_{\overline{\Lambda}})$ is expected. A non-zero value of $A_{\Xi\Lambda}$ would be unambiguous evidence for direct CP violation. A brief review of CP violation in hyperon decays is given, the *HyperCP* spectrometer is described, and the status of the analysis and future prospects are discussed.

1. Introduction

In the 35 years since the discovery of CP violation our understanding of the phenomenon has improved little despite a long series of beautiful experiments. Experimentally it remains a small peculiarity unique to a few decays of the K_L. In the standard model CP violation lies with the complex phase in the Cabbibo–Kobayashi–Maskawa (CKM) matrix. The origin of this phase, if it exists, remains a mystery. If our theoretical prejudices are correct, CP violation should appear outside of the decay of the K_L, and should express itself directly in the weak decays of hadrons, and not only indirectly through the mixing between particle and anti-particle. It is vital to confirm these theoretical expectations and determine experimentally whether CP violation is a universal property of the weak interaction, and whether direct CP violation exists.

Large experimental efforts have been underway for some twenty years to search for direct CP violation in kaon decays, and the search for CP violation in B decays will commence in earnest with the next generation of electron-positron and hadron colliders. There is, however, another promising arena in which to look for direct CP violation, and CP violation outside of the neutral kaon system: in the nonleptonic decays of strange baryons, or hyperons. This is the goal of *HyperCP*, the first *dedicated* hyperon CP violation experiment, which will probe hyperon CP violation through the decays $\Xi^- \to \Lambda\pi^-$, $\Lambda \to p\pi^-$ and $\overline{\Xi}^+ \to \overline{\Lambda}\pi^+$, $\overline{\Lambda} \to \overline{p}\pi^+$.

2. Signatures for Hyperon CP Violation

The phenomenology of CP violation in hyperon decays has been discussed in several excellent references (see Ref. [1] for example). We briefly review it here. Conservation of angular momentum allows both S- and P-wave final states in hyperon two-body decays. Since the parity of the final state is $(-1)^{L+1}$, only the P-wave final state would be allowed if parity were conserved. It is not and the decay can go into admixtures of both S- and P-wave final states:

$$\begin{aligned} S &= +\sum_i S_i e^{i(\delta_i^S+\phi_i^S)}, \\ P &= +\sum_i P_i e^{i(\delta_i^P+\phi_i^P)}, \\ \overline{S} &= -\sum_i S_i e^{i(\delta_i^S-\phi_i^S)}, \\ \overline{P} &= +\sum_i P_i e^{i(\delta_i^P-\phi_i^P)}, \end{aligned} \quad (1)$$

*Representing the *HyperCP* collaboration: R.A. Burnstein, A. Chakravorty, A. Chan, Y.C. Chen, W.S. Choong, K. Clark, M. Crisler, J. Drapala, E.C. Dukes, C. Durandet, J. Felix, G. Gidal, H.R. Gustafson, C. Ho, T. Holmstrom, M. Huang, C. James, M. Jenkins, D.M. Kaplan, L.M. Lederman, N. Leros, M.J. Longo, F. Lopez, G. Lopez, W. Luebke, K.B. Luk, K.S. Nelson, J.P. Perroud, D. Rajaram, H.A. Rubin, J. Sheng, M. Sosa, P.K. Teng, B. Turko, J. Volk, C.G. White, S.L. White, C. Yu, Z. Yu, and P. Zyla.

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HYPERONS AND NEUTRINOS
SECTION 7

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7. HYPERONS AND NEUTRINOS

7.1 INTRODUCTION

In the beginning, at Fermilab, there were neutrinos and hyperons created by beams from the Main Ring. Among the first experiments proposed, approved, and run were E1A, and E21, the first generation of Fermilab electronic neutrino detectors, and E8 the first generation Fermilab hyperon beam experiment. There were also several bubble chamber exposures in the neutrino beam. These approaches matured into complete programs of experiments in the Tevatron fixed target era.

The common physics thread shared by these two rather different beam particles is the weak interaction. Neutrinos are particles which feel only the weak force. This makes them excellent probes of complicated structures, like protons and neutrons. Some of the Tevatron neutrino experiments were so sharply focused in the area, that they have been included in the section on proton, neutron, and meson structure rather than here. Neutrinos are also excellent places to study the weak interaction itself. They don't do anything else, so they are a clean weak interaction laboratory. Neutrino scattering cross-sections (the probability that they will actually hit something in a given target) increase linearly with the neutrino energy. This made the 400 GeV Fermilab Main Ring good for doing neutrino physics, and the 800 GeV/c Tevraton even better.

The hyperons are the particles in the same family as the proton and the neutron, but containing one or more strange valence quarks. Only the weak interaction does not conserve strangeness; it is the only way a hyperon can decay. This makes hyperons live 10^{14} times longer than their non-strange cousins, the excited non-strange proton and neutron states. This is long enough to make hyperon beams that will go many meters at Tevatron energies before most of the hyperons decay. Hyperons, like protons, are particles of spin ½. This makes it possible to have polarized hyperon beams; something which is impossible with a spin 0 K meson beam. Polarization is a delicate and sensitive probe of both the weak interaction controlling the hyperon's decay and the structure of the quarks and other stuff which makes up the hyperon itself. E8 discovered in 1976 that hyperons were produced with significant polarization. Tom Devlin, of Rutgers University, and Lee Pondrom, of the University of Wisconsin, were subsequently awarded the Panofsky prize for this discovery and the sequence of experiments it enabled.

Typically only one process happens at a time in weak interactions, one quark decays to another, or a neutrino hits just one quark in a target proton. The combination of the cleanliness of the weak interaction and the high intensity beams of both neutrinos and hyperons available at the Tevatron allowed a set of experiments of unprecedented precision.

A carefully crafted experiment can isolate just one particular aspect of the structure of a proton in order to study it carefully. For example, the E632 dimuon result focused in on the charmed quark content of the proton - which only exists in the *sea* of virtual quark antiquark pairs inside the proton. In a similar but different example, in a series of experiments all the hyperon magnetic moments were measured with high precision, including the Ω^- (by E800) which is made of three strange valence quarks. The results are sufficiently precise to both confirm our basic understanding of the structure of the baryons (the family to which protons, neutrons and hyperons belong) and to confound theoretical description anywhere close to the present experimental uncertainties.

E815/NuTeV will make a precision measurement of the Weinberg angle, $\sin^2(\theta_W)$, a fundamental electro-weak parameter more normally associated with the very high energy scales of e^+e^- and hadron colliders. E872 is seeking to observe the last fundamental fermion, the τ neutrino.

7.2 E632 - AN EXPOSURE OF THE 15' BUBBLE CHAMBER WITH A NEON-MIXTURE TO A WIDEBAND NEUTRINO BEAM FROM THE TEVATRON

Birmingham (Great Britain), UC/Berkeley, CERN (Switzerland), Fermilab, Hawaii, IHEP/Serpukhov (Russia), IIT, Imperial College (Great Britain), ITEP (Russia), Jammu (India), Libre (Belgium), MPI (Germany), Moscow State (Russia), Oxford (Great Britain), Panjab (India), Rutgers, Saclay (France), Stevens, Tufts

E632 was the only Bubble Chamber experiment to study neutrinos at Tevatron energies. These neutrinos were produced by 800 GeV/c protons, using a quadrupole triplet beam. A moderately heavy neon-hydrogen mix was selected to increase both the event rate and detection of gammas, electrons, and pi-zeros. Holography and a high resolution camera improved heavy flavor detection in the central portion of the fiducial volume. The new External Muon Identifier and Internal Picket Fence helped separate charged and neutral currents and select dilepton events. Bubble Chambers use the same fluid for both target and detector, which provides unbiased detection of secondaries in all directions and down to short distances.

In addition to searching for new phenomena in the higher energy region, dimuon, neutral current, strange and charmed particle production were studied. Other topics were coherent pion and ρ-meson production and nuclear effects in experiments using neon.

E632 Degree Recipients

Homaira Akbari	Ph.D.	Tufts University
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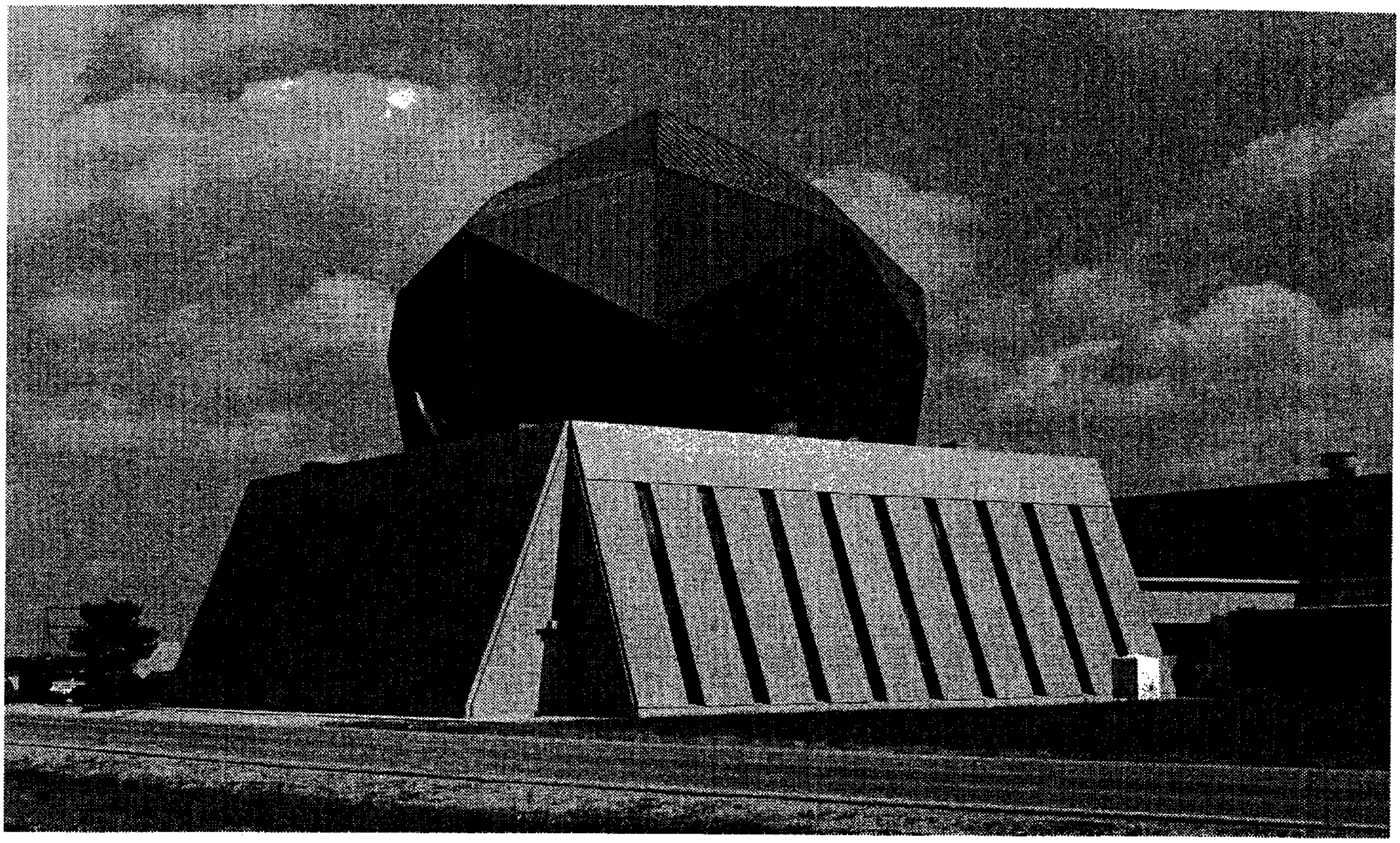
Douglas Francis DeProspo	Ph.D.	Rutgers University
Mary Anne Lauko	Ph.D.	Rutgers University
P.R. Nailor	Ph.D.	Imperial College - London
Elena Vataga	Ph.D.	Moscow State University
L. Verluyten	Ph.D.	Universiteit Antwerpen
Stephane Willocq	Ph.D.	Tufts University



E632 Publications

Coherent Production of π Mesons by Charged Current Interactions of Neutrinos and Antineutrinos on Neon Nuclei at the Tevatron., M. Aderholz, *et al.*, Phys. Rev. Lett. **63**, 2349 (1989).
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Coherent production of single pions and rho mesons in charged-current interactions of neutrinos and antineutrinos on neon nuclei at the Fermilab Tevatron., S. Willocq, *et al.*, Phys. Rev. **D47**, 2661 (1993).
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Dimuon production by neutrinos in the Fermilab 15-ft bubble chamber at the Tevatron

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The Fermilab 15-ft bubble chamber has been exposed to a quadrupole triplet neutrino beam produced at the Tevatron. The ratio of ν to $\bar{\nu}$ in the beam is approximately 2.5. The mean event energy for ν-induced charged-current events is 150 GeV, and for $\bar{\nu}$-induced charged-current events it is 110 GeV. A total of 64 dimuon candidates (1 $\mu^+\mu^+$, 52 $\mu^-\mu^+$ and $\mu^+\mu^-$, and 11 $\mu^-\mu^-$) is observed in the data sample of approximately 13 300 charged-current events. The number and properties of the $\mu^-\mu^-$ and $\mu^+\mu^+$ candidates are consistent with their being produced by background processes, the important sources being π and K decay and punchthrough. The 90%-C.L. upper limit for $\mu^-\mu^-/\mu^-$ for muon momenta above 4 GeV/c is 1.2×10^{-3}, and for momenta above 9 GeV/c this limit is 1.1×10^{-3}. The opposite-sign-dimuon–to–single-muon ratio is $(0.62\pm0.13)\%$ for muon momenta above 4 GeV/c. There are eight neutral strange particles in the opposite-sign sample, leading to a rate per dimuon event of 0.65 ± 0.29. The opposite-sign-dimuon sample is consistent with the hypothesis of charm production and decay.

I. INTRODUCTION

The Fermilab 15-ft bubble chamber was exposed to a high-energy neutrino beam at the Tevatron (experiment E632) and data were collected during two separate runs. The neutrino energy spectrum extended to greater than 600 GeV, and approximately one-third of the neutrino interactions were at energies above 200 GeV. A big bubble chamber is a well-understood and reasonably unbiased detector and thus well suited to a search for new phenomena, which is the primary aim of the present experiment. Multilepton events may indicate the presence of new particles, and in this paper we report results on ν- and $\bar{\nu}$-induced dimuon events in the data collected during the first run.

Opposite-sign-dilepton [$\mu\mu$ (Refs. 1–9) and μe (Refs.

7.3 E715 - PRECISION MEASURMENT OF $\Sigma^- \rightarrow n e^- \nu$

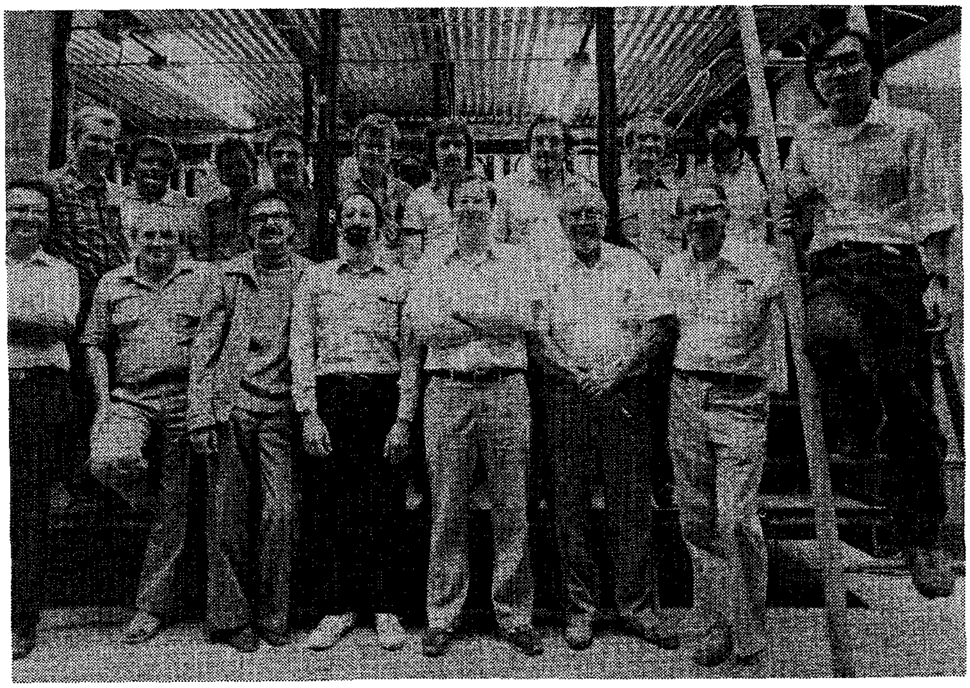
University of Chicago, Elmhurst College, Fermi National Accelerator Laboratory, Iowa State University, Leningrad Institute of Nuclear Physics (USSR) Yale University

The Charged Hyperon Collaboration was one of the groups using high energy hyperon beams at the Tevatron to study the mechanisms by which hyperons are produced and decay. These three experiments, E715, E761, and E781, shared a largely constant set of, now senior physicists and the the Proton Center charged hyperon beam which was built in the Main Ring era for the original hyperon experiment, E497.

A hyperon is a baryon, a relative of the proton, which contains at least one strange quark and decays by the weak interaction. The decays of these particles provide insights into the structure of the baryon family that are inaccessible with other techniques. The fundamental questions are basic: "what are these things made of and how are they put together?" The discovery, by E8 in 1976, that hyperons are produced polarized makes the hyperon beam a sensitive and unique probe for this type of physics. E715, the first experiment to use the Tevatron during its 400 GeV commissioning run in 1983, resolved a long standing and potentially serious anomaly in the beta decay of the Σ^- hyperon; $\Sigma^- \rightarrow n e^- \nu$. In four previous measurements, the angular correlation of the electron direction relative to the Σ^- spin had the "wrong" sign. If these observations were confirmed, then the decay was either due to a new weak interaction (right handed W's, in the jargon) or the accepted spin structure of the Σ^-, and by extension the whole baryon family, was just wrong. Never-mind. With 100 times the previous world's data, E715 contradicted the old measurements and got the expected sign and magnitude of the electron correlation. E715 also made precision measurements of the magnetic moments of both the Σ^- and Ξ^-, and made significant contributions to the development of transition radiation detectors (TRDs) as high performance electron identifiers.

E715 Degree Recipients

Shao Hsueh	Ph.D.	University of Chicago
Panos Andreo Razis	Ph.D.	Yale University
L.H. Trost	M.S.	University of Iowa
G. Zapalac	Ph.D.	University of Chicago



E 715 IS HONORED AND PROUD TO BE

THE FIRST ENERGY SAVER USER

OCTOBER 1, 1983

THANK YOU FERMILAB!

E715 Publications

Measurement of the Electron Asymmetry in the Beta Decay of Polarized Σ^- Hyperons. , S.Y. Hsueh, *et al.*, Phys. Rev. Lett. **54**, 2399 (1985).
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Measurement of the Electron Asymmetry in the Beta Decay of Polarized Σ^- Hyperons

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We report the results of a Fermilab Tevatron experiment using a Σ^- beam with a measured polarization of 0.22 ± 0.04. We find the electron asymmetry in Σ^- beta decay to be $\alpha_e = -0.53 \pm 0.14$ on the basis of a sample of 25 000 events, in agreement with the Cabibbo model and in contradiction with previous experiments. The corresponding value for the ratio of axial-vector to vector form factors is $g_1/f_1 = -0.29 \pm 0.07$.

PACS numbers: 13.30.Ce, 14.20.Jn

The electron asymmetry α_e in Σ^- beta decay is highly sensitive to the ratio of axial-vector to vector form factors g_1/f_1 (see Fig. 1). The magnitude $|g_1/f_1|$ is obtained from unpolarized decays; two recent high-statistics experiments[1,2] combined give $|g_1/f_1| = 0.36 \pm 0.04$.

A recent fit of beta-decay data in the baryon octet by the Cabibbo model[3] predicts[4] for $\Sigma^- \rightarrow ne\bar{\nu}$, $g_1/f_1 = -0.28 \pm 0.02$, which corresponds to a large negative electron asymmetry $\alpha_e = -0.51 \pm 0.04$ (Fig. 1). In fact, of all the hyperons, $\Sigma^- \rightarrow ne\bar{\nu}$ is the only accessible decay for which the Cabibbo model predicts a relative sign which is *opposite* to that familiar from neutron or lambda beta decay. Previous experiments with polarized Σ^- have failed to confirm this distinctive test of the theory; the electron asymmetry averaged over four earlier experiments[5-8] totaling 352 events is $\alpha_e = 0.26 \pm 0.19$. An attempt was made[1] to infer the sign of g_1/f_1 from the shape of the electron energy spectrum. This analysis favored the negative sign. However, the dependence of the electron spectrum on g_1/f_1 is both small and sensitive to the choice of f_2 and to radiative corrections.

The high flux of polarized Σ^- available[9] with the Fermilab Tevatron made it possible to study Σ^- beta decay on a statistical level far beyond that of previous experiments. In our experiment we detected 90 000 Σ^- beta decays. This Letter reports a g_1/f_1 sign determination based on an initial sample of 25 000 events.

In the experimental configuration shown in Fig. 2, 400-GeV/c protons from the Fermilab Tevatron were incident on a copper target placed at the upstream end of the hyperon channel.[10] The 250-GeV/c secondary beam emerging from the magnet was limited to an emittance of ± 16 GeV/c and 1 μsr; its composition was about 10% Σ^-, 0.5% Ξ^-, and the rest mostly π^-. By an appropriate setting of the incident proton angle in the horizontal plane, hyperons were produced polar-

7.4 E756 - Magnetic Moment of the Ω^- Hyperon

Fermilab, Michigan, Minnesota, Rutgers, Washington

In E756, polarizations of the omega minus and the other charged hyperons inclusively produced by 800 GeV protons were measured. Contrary to predictions, E756 discovered that anti-cascade plus was signficantly polarized when produced in these interactions. This remains one of the mysteries in strong interactions. The details of the cascade minus polarization were also studied. We found it has a different behavior from that of the lambda hyperon. With these polarized cascade minus events and their anti-particles, E756 measured and compared their magnetic moments. E756 also performed the first CP-violation search in charged-cascade decay.

On the other hand, omega-minus hyperons created by protons did not get polarized. Another approach was employed. With a polarized neutral beam, a polarized sample of omega minus's was obtained, and the magnetic moment of the omega minus was measured for the first time. E756 also collected about 2000 anti-omega plus decays, with which E756 determined the lifetime, decay parameter, and mass of this rare anti-hyperon.

E756 Degree Recipients

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Pak Ming Ho	Ph.D.	University of Michigan
An Nguyen	Ph.D.	University of Michigan

E800 Publications

Production Polarization of Magnetic Moment of Ξ^+ Antihyperons Produced by 800 GeV/c Protons., P.M. Ho, *et al.*, Phys. Rev. Lett. **65**, 1713 (1990).
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Polarization of Ξ^- Produced by 800 GeV Protons., J. Duryea, *et al.*, Phys. Rev. Lett. **67**, 1193 (1991).
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Production Polarization and Magnetic Moment of $\bar{\Xi}^+$ Antihyperons Produced by 800-GeV/c Protons

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The polarization of $\bar{\Xi}^+$ hyperons produced by 800-GeV/c protons in the inclusive reaction $p+\mathrm{Be}\to\bar{\Xi}^+ + X$ has been measured. The average polarization of the $\bar{\Xi}^+$, at a mean $x_F=0.39$ and $p_t=0.76$ GeV/c, is $-0.097\pm0.012\pm0.009$. The magnetic moment of the $\bar{\Xi}^+$ is $0.657\pm0.028\pm0.020$ nuclear magneton.

PACS numbers: 13.88.+e, 13.40.Fn, 13.85.Ni, 14.20.Jn

In 1976 it was shown[1] that Λ hyperons are substantially polarized when they are produced in the reaction $p+\mathrm{Be}\to\Lambda+X$. Similarly, polarization of comparable magnitude has been found in the production of Σ^0, Σ^+, Σ^-, Ξ^0, and Ξ^- hyperons.[2] The polarization of $\bar{\Lambda}$'s produced by protons has been found to be consistent with zero.[3] Models based on the recombination of valence quarks in the projectile with quarks from the sea to form the hyperon[4] have been used to explain the qualitative behavior shown by the data. These models also predict zero polarization for particles that have no valence quarks in common with the incoming particle.

We have discovered that $\bar{\Xi}^+$'s produced by protons have a polarization approximately equal to that of the Ξ^-. The presence of a significant polarization for the $\bar{\Xi}^+$ makes possible the first measurement of the magnetic moment of an antihyperon.

This experiment was performed in the Proton Center beam line at Fermilab. A plan view of the experiment is shown in Fig. 1. An 800-GeV/c proton beam was incident on a $2\times2\times92$-mm^3 beryllium target with vertical production angles of ±2.4 mrad. By comparing the transverse-momentum (p_t) distributions of the detected particles at each angle, the relative difference of the two targeting angles was determined to be less than 0.06 mrad. A secondary beam of charged particles was defined by a curved collimator through the magnet $M1$. With a field integral, $\int B\,dl$, of 15.35 T m, $M1$ was used to transmit positively charged particles with momenta in the range from 240 to 450 GeV/c and to precess the spin of the particles. Negatively charged particles were selected by reversing the magnetic field. A polarization perpendicular to the production plane would be precessed in the x-z plane by $M1$. A y component of the polarization would violate parity conservation in strong interactions.

In this experiment the decay sequences of interest were $\bar{\Xi}^+\to\bar{\Lambda}\pi^+, \bar{\Lambda}\to\bar{p}\pi^+$ and $\Xi^-\to\Lambda\pi^-, \Lambda\to p\pi^-$. The charged particles were detected with a spectrometer consisting of scintillation counters $S1$, $S2$, $V1$, $V2$, and M, silicon strip detectors SSD1–SSD8, multiwire chambers $C1$–$C9$, and analyzing magnet $M2$ that provided a transverse bending power of 1.5 GeV/c in the horizontal plane. For the $\bar{\Xi}^+$ run, the magnetic field of $M2$ bent π^+'s to the $-x$ direction and $\bar{p}$'s to the $+x$ direction. The trigger required a signal from counters $S1$ and $S2$ with no signal from the veto counters $V1$ and $V2$. The pulse height from the multiplicity counter M was required to be greater than that corresponding to

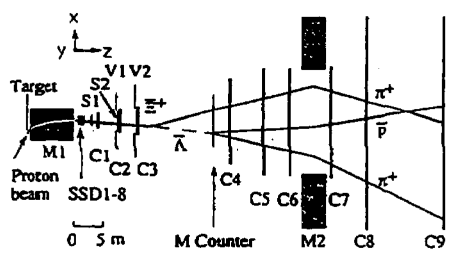

FIG. 1. Plan view of the experiment. Note that the transverse dimensions have been exaggerated. SSD1–SSD8, $C1$–$C3$, and $C4$–$C9$ have 0.1-, 1-, and 2-mm pitch, respectively. The SSD's are grouped into four pairs of x and y planes. The y axis is in the production plane and out of page in this figure, z is along the axis of the charged beam through the spectrometer, and the x axis is in the horizontal plane to form a right-handed coordinate system.

7.5 E761 - AN ELECTROWEAK ENIGMA: HYPERON RADIATIVE DECAYS

Bristol (Great Britain), CBPF (Brazil), Fermilab, IHEP/Beijing (PRC), Iowa, ITEP/Moscow (Russia), PNPI (Russia), Rio de Janeiro (Brazil), Sao Paulo (Brazil), Yale

E761 was the third experiment done by the Charged Hyperon Collaboration in the series E497, E715, E761, E781. It built upon the previous two experiments in several ways. The techniques of producing, reversing, and measuring the polarization of charged hyperon beams had been well developed and applied to rare Σ^- decays in E715. The members of the collaboration had also advanced the state of the art in electron-pion separation using transition radiation detectors (TRDs), applying these techniques to make a tracking photon detector for radiative hyperon decays. The high energy decay photons from the hyperon radiative decays were converted in steel plates, and the resulting shower centroid was tracked using TRDs to sense the high energy electrons and the positrons. The main interest was in the Σ^+ radiative decay. Since to the positive Σ^+ hyperon occurs as only a few percent of a beam which is mostly protons we had to handle significantly higher rates through the apparatus than in E715. Advances in data acquisition made this relatively straight forward by 1990 when E761 took it data.

The decay modes studied in E761 were the hyperon radiative decays; $\Sigma^+ \rightarrow p\,\gamma$, $\Xi^- \rightarrow \Sigma^- \gamma$ and $\Omega^- \rightarrow \Xi^- \gamma$. These decays require Strong, weak and electro-magnetic interactions. The parity violation observed here is very large and difficult to understand theoretically. E761 made the most precise measurements of the branching ratio and asymmetry parameter in both Σ^+ and Ξ^- radiative decays. It also set an upper limit on the branching ratio of the Ω^- radiative decay. In addition to the largest samples of these unusual decay modes E715 also made precision measurements of the production polarization, magnetic moments and lifetimes of the Σ^+ hyperon and its anti particle. E715 saw that the anti-Σ^+ was produced polarized, an effect even more surprising than hyperon polarization. E715 has also made the first experimental observation of the magnetic moment precession of Σ^+ hyperons channeled in bent crystals, and even a search for supersymmetric hyperons.

E761 Degree Recipients

Ivone Alburquerque	Ph.D.	University of Sao Paulo
Ricardo .F. Barbosa	M.S.	University of Sao Paulo
Dong Chen	Ph.D.	State University of New York at Albany
Tim Dubbs	Ph.D.	University of Iowa
Maurice Emile Foucher	Ph.D.	Yale University
Gery Langlund	Ph.D.	University of Iowa
Jose Roberto Pinheiro Mahon	Ph.D.	University of Sao Paulo
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Steve Timm	Ph.D.	Carnegie Mellon University

E761 Publications

Measurement of the asymmetry parameter in the hyperon radiative decay $\Sigma^+ \to p\gamma$, M. Foucher *et al.*, Phys. Rev. Lett. **68**, 3004 (1992).
First observation of magnetic moment precession of channeled particles in bent crystals., D. Chen, *et al.*, Phys. Rev. Lett. **69**, 3286 (1992).
Polarization of Σ^+ and anti-Σ^- hyperons hyperons produced by 800-GeV/c protons., A. Morelos, *et al.*, Phys. Rev. Lett. **71**, 2172 (1993).
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P_t and X_F dependence of the polarization of Σ^+ hyperons produced by 800 GeV/c protons., A. Morelos, *et al.*, Phys. Rev. **D52**, 3777 (1995).
New upper limit for the branching ratio of the $\Omega^- \to \Xi^- \gamma$ radiative decay., I.F. Albuquerque, *et al.*, Phys. Rev. **D50**, 18 (1994).
Measurement of the branching ratio and asymmetry parameter for $\Sigma^+ \to p\gamma$ radiative decay., S. Timm, *et al.*, Phys. Rev. **D51**, 4638 (1995).
A Search for light supersymmetric baryons, I.F. Albuquerque, *et al.*, Phys.Rev.Lett.**78**, 3252 (1997).
Measurement of the anti-Σ^+ lifetime and direct comparison with the Σ^+ lifetime., R.F. Barbosa, *et al.*, Phys. Rev. **D61**, 031101 (2000).

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Measurement of the Asymmetry Parameter in the Hyperon Radiative Decay $\Sigma^+ \to p\gamma$

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(Received 5 March 1992)

We have measured the asymmetry parameter (α_γ) in the hyperon radiative decay $\Sigma^+ \to p\gamma$ with a sample of 34754 ± 212 events obtained in a polarized charged hyperon beam experiment at Fermilab. We find $\alpha_\gamma = -0.720 \pm 0.086 \pm 0.045$, where the quoted errors are statistical and systematic, respectively.

PACS numbers: 13.40.Hq, 14.20.Jn

Hyperon radiative decays represent a class of baryon decays which require contributions from both the weak and electromagnetic interactions. Hara proved in 1964 [1] that the asymmetries in radiative hyperon decay vanish in the SU(3) limit, assuming only *CP* invariance and left-handed currents in the weak interaction. Contrary to this prediction, the first measurements of the asymmetry parameter in the decay $\Sigma^+ \to p\gamma$ revealed some evidence for large negative asymmetries ($\alpha_\gamma = -1.03^{+0.52}_{-0.42}$ [2], -0.53 ± 0.36 [3]). These were bubble chamber experiments where polarized Σ^+ were produced from the low-energy $K^- p \to \Sigma^+ \pi^-$ reaction. The average Σ^+ polarization was about 40%.

The main difficulty in such experiments is separation of the $\Sigma^+ \to p\gamma$ radiative decay from the 400 times more abundant hadronic decay $\Sigma^+ \to p\pi^0$. Moreover, the asymmetry parameter in the hadronic decay is large and negative ($\alpha_{\pi^0} = -0.980 \pm 0.016$ [4]), which raised the concern that the observed asymmetry in the $\Sigma^+ \to p\gamma$ decay might be, in fact, due to some contamination of the background into the $p\gamma$ sample. In addition, the number of $p\gamma$ events detected in both experiments was very small (61 [2] and 46 [3], respectively).

These observations raised a wide interest among theorists [5]. Various models were investigated. None of these models could describe satisfactorily both the large negative asymmetry and the observed rate of the $\Sigma^+ \to p\gamma$ decay. This became possible only recently in the form of a QCD sum-rule model [6].

A new measurement of the $\Sigma^+ \to p\gamma$ asymmetry was performed in 1987 at KEK in a counter experiment [7] with Σ^+ produced in the reaction $\pi^+ p \to \Sigma^+ K^+$. The polarization of the Σ^+ was about 87%. From a sample of 190 events the asymmetry parameter was found to be -0.86 ± 0.13(stat) ± 0.04(syst).

This experiment (E761) [8] was designed to perform a measurement of the asymmetry parameter in the $\Sigma^+ \to p\gamma$ decay on a high statistical level and with reliable separation from the $\Sigma^+ \to p\pi^0$ mode. The high-energy hyperon beam at Fermilab provided a large flux (≈ 2000/sec) of Σ^+ with a polarization of 12%. The direction of the polarization was periodically reversed to allow the separation of the asymmetry from instrumental biases. To identify the $\Sigma^+ \to p\gamma$ decay we used charged-particle spectrometers that provided high-precision measurements of the missing neutral mass. In addition, a special photon spectrometer was constructed to determine the direction and energy of the photons.

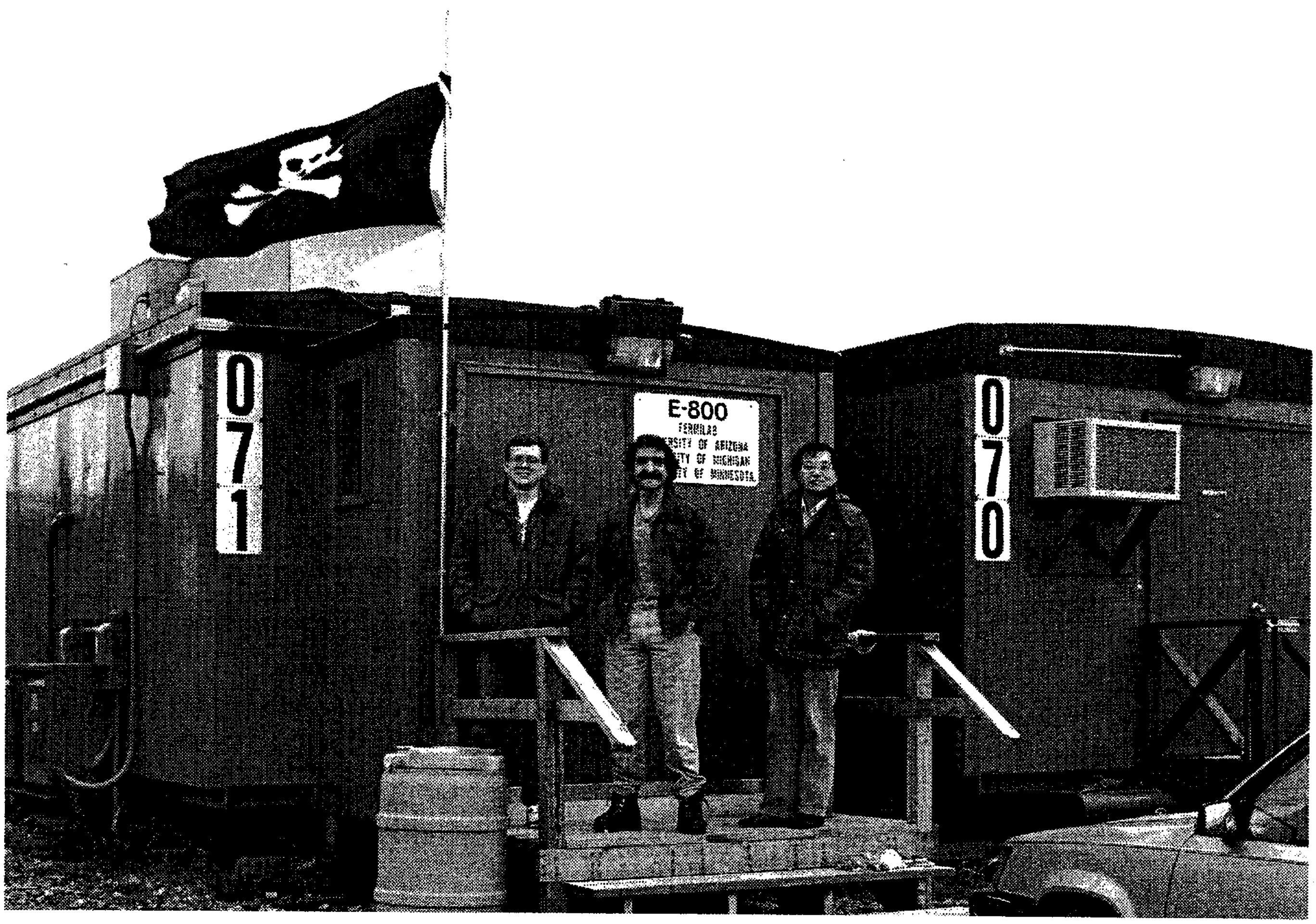
The experiment was located in the Proton Center beam line at Fermilab. The apparatus (Fig. 1) has four parts:

7.6 E800 - HIGH PRECISION MEASUREMENT OF THE Ω^- MINUS MAGNETIC MOMENT

Arizona, Depauw, Fermilab, Michigan, Minnesota

The primary goal of E800 was to make a precision measurment of the Ω^- hyperon magnetic moment. The simple quark and spin structure of the Ω^- (three strange quarks with spins aligned) makes it an ideal testing ground for theories that describe the behaviour of quarks inside hadrons. Polarized Ω^-'s were produced by a new technique that involved using a secondary, unpolarized neutral hyperon beam to create them. Spin precession of this polarized Ω^- - sample was then used to determine the Ω^- magnetic moment.

Using a sample of 2.35×10^5 polarized Ω^-, the Ω^- magnetic moment was measured to be $\mu = -2.024 \pm 0.056$ n.m. Other physics results produced by the experiment include detailed studies of the polarization processes in hyperon production and a measurement of the Ω^- decay asymmetry parameters.



E800 Degree Recipients

Gerald Michael Guglielmo	Ph.D.	University of Minnesota
Noah Benjamin Wallace	Ph.D.	University of Minnesota
D.M. Woods	Ph.D.	University of Minnesota

E800 Publications

Precision Measurement of the Ω^- Magnetic Moment, N.B. Wallace, *et al.*, Phys. Rev. Lett. **74**, 3732 (1995).
Polarization of the Ξ^- and Ω^- Hyperons Produced by Neutral Beams., D.M. Woods, *et al.*, Phys. Rev. **D54**, 6610 (1996).

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Precision Measurement of the Ω^- Magnetic Moment

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Using a sample of 2.35×10^5 polarized $\Omega^- \rightarrow \Lambda K^-$ decays, we have measured the Ω^- magnetic moment to be $\mu_{\Omega^-} = (-2.024 \pm 0.056)\mu_N$.

PACS numbers: 13.40.Em, 13.30.Eg, 14.20.Jn

The structure of baryons can be probed at long range by measuring their magnetic moments. For example, the ratio of the proton and neutron magnetic moments offered early support for the quark model of baryons. There now exist precise measurements of the magnetic moments of the Λ [1], Σ^+ [2,3], Σ^- [4,5], Ξ^0 [6,7], and Ξ^- [8–10], as well as the $\overline{\Xi}^+$ [11] and $\overline{\Sigma}^-$ [3] antihyperons. Together with the very precisely measured proton and neutron moments, these measurements have been used to test models of baryon structure [12]. Such models have only been successful to the 10% level, perhaps because these baryons have a more complex structure than expected. A measurement of the Ω^- magnetic moment is of interest due to its simple valence quark structure (three strange quarks with their spins aligned). Because of this symmetry, and because the Ω^- has no light valence quarks (u or d), this system is expected to have smaller relativistic and orbital angular momentum corrections than may be present in the octet baryons [13]. The only previous measurement of the Ω^- magnetic moment [14], to a precision of 10%, could not clearly differentiate between models of baryon structure.

The traditional spin-precession technique for measuring hyperon magnetic moments uses a beam of polarized hyperons produced from proton interactions [1,15]. The hyperon spin is then precessed in a magnetic field and the final spin direction is measured from the asymmetry of the distribution of the hyperon decay products. Unlike the spin $\frac{1}{2}$ hyperons, Ω^-'s produced by protons are unpolarized [16]. In this experiment polarized Ω^-'s were produced by using two different techniques: the spin transfer technique from a polarized neutral beam (PNB), which was used in the previous Ω^- magnetic moment measurement [14], and a new technique that used an unpolarized neutral beam (UNB) [17]. In both cases a neutral beam containing Λ and Ξ^0 hyperons, as well as γ's, neutrons, and K^0's, was produced by an 800 GeV/c proton beam in the inclusive reaction $p + \text{Be} \rightarrow$ (neutral particle) $+X$. In the unpolarized neutral beam mode, the protons struck an upstream target at 0 mrad. The resulting particles passed through a collimator embedded in a sweeping magnet with a field integral of 10.9 T m. This neutral beam was then targeted at vertical production angles of ± 1.8 mrad on a second Be target to produce Ω^-'s primarily by the reaction $(\Lambda, \Xi^0) + \text{Be} \rightarrow \Omega^- + X$. The polarized neutral beam was produced by targeting the proton beam at vertical targeting angles of ± 1.8 mrad, producing polarized Ξ^0 and Λ [18,19]. Since the sweeping magnet field was perpendicular to the production plane, the spins of the neutral particles were not precessed as they passed through the channel. The Ω^-'s were then produced by targeting the polarized neutral beam at 0 mrad. Table I shows the average polarizations for each of these modes. The Ω^- yield per incident proton for unpolarized neutral beam production was roughly 3 times that for polarized neutral beam production.

The Ω^- production target (Be, $5.14 \times 5.28 \times 147$ mm^3) was located 55 cm upstream from the spin-precession-momentum-selection magnet. The magnet was 7.315 m long with a field in the $-\hat{y}$ direction. The magnet was fitted with a curved brass and tungsten

TABLE I. The sample sizes and average polarizations measured for the three Ω^- samples used in this analysis. The initial polarization is in the $\pm\hat{x}$ direction in a right-handed coordinate system defined by the Ω^- momentum direction ($\hat{z}$) and the vertical ($\hat{y}$).

Production method	Precession field integral (T m)	Sample size 10^4 events	P_{Ω^-}
UNB	-24.36 ± 0.26	16.7	0.044 ± 0.008
UNB	-17.48 ± 0.17	5.02	0.036 ± 0.015
PNB	-24.36 ± 0.26	1.83	-0.069 ± 0.023

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7.7 E815/NuTeV - Precision Neutrino / Antineutrino Deep Inelastic Scattering Experiment

Cincinnati, Columbia, Fermilab, Kansas State, Northwestern, Oregon, Rochester, Xavier

To make progress on precision tests of the standard model after E744/770 required the use of a new technique, employing separate neutrino and antineutrino beams. Measuring the weak mixing angle using these separate beams was a major goal of E815, the NuTeV experiment. The beam was delivered by the sign-selected quadrupole train (SSQT) beamline. This chain of magnets generated a beam made up either solely of neutrinos or solely of antineutrinos, produced by focusing either positively-charged secondaries (which decay into neutrinos) or negative ones, (which yield a beam of antineutrinos). The new beamline was matched to a refurbished Lab E detector, provided with new scintillator oil and photomultiplier tubes in the calorimeter, and an instrumented decay channel upstream of the main detector to look for new particles outside the standard theory. To establish the energy scale of the calorimeter and continuously calibrate its response, a second beam line was constructed to deliver a test beam of electrons, muons, and pions to the detector.

NuTeV collected data during the 1996-1997 Tevatron Fixed Target run. Analysis of the data is currently well underway. By comparing the relative event rates of neutral current (Z-exchange) and charged current (W-exchange) interactions in neutrino and antineutrino beams, NuTeV has measured the weak mixing angle with a precision comparable to collider measurements. (See G. Zeller et al., DPF99, hep-ex/9906024.) The fact that NuTeV's result is consistent with those from very different processes provides an impressive confirmation of the standard model across many momentum scales, and imposes an important constraint on new physics. First results have also recently been published on the search for heavy neutrinos that are expected in many theoretical models. No indication of such neutrinos was seen in the mass region below 2.2 GeV. Another search has placed limits on the existence of a new particle suggested by an anomaly observed in the KARMEN experiment in England.

In addition to the main goal of NuTev, many other physics topics are being studied, including setting competitive limits on neutrino oscillations for muon to electron neutrinos; measuring the distribution of strange quarks in the nucleon (the "strange sea"); and determining cosmic ray muon energies in a new way. The measurements of quark momentum distributions from CCFR/NuTeV's nucleon structure function determinations provide an important fundamental input to theory and to other experiments.

This trio of neutrino experiments using the Lab E detector has contributed greatly to present understandings of both the weak and the stong interactions, and has searched for new phenomena beyond the current standard theory. The extraordinary vitality and success of this program is evident in the depth and breadth of physics topics it has addressed.

E815 Degree Recipients

Artur Vaitaitis	Ph.D.	Columbia University

E815 Publications

Search for Neutral Heavy Leptons in a High-Energy Neutrino Beam., A. Vaitaitis, *et al.*, Phys. Rev. Lett. **83**, 4943 (1999).
Evidence for Diffractive Charm Production in ν_μ Fe and anti-ν_μ Fe Scattering at the Tevatron., T. Adams, *et al.*, Phys. Rev. **D61**, 92001 (2000).
Search for a 33.9 Mev/c^2 Neutral Particle in Pion Decay., J.A. Formaggio, *et al.*, Submitted to Phys. Rev. Lett. **84**, 4043 (2000).

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Search for a 33.9 MeV/c^2 Neutral Particle in Pion Decay

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The E815 (NuTeV) neutrino experiment has performed a search for a 33.9 MeV/c^2 weakly interacting neutral particle produced in pion decay. Such a particle may be responsible for an anomaly in the timing distribution of neutrino interactions in the KARMEN experiment. E815 has searched for this particle's decays in an instrumented decay region; no evidence for this particle was found. The search is sensitive to pion branching ratios as low as 10^{-13}.

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The KARMEN collaboration at the ISIS spallation neutron facility at the Rutherford Appleton Laboratory uses a pulsed neutrino beam resulting from stopped pion and muon decays to study neutrino-nucleon interactions. Their experiment has reported an anomaly in the timing distribution of neutrino interactions from stopped muon decays [1]. One possible explanation for the anomaly is an exotic pion decay, where a neutral weakly interacting or sterile particle is produced and travels 17.7 m to the KARMEN detector with a velocity of 4.9 m/μs. Upon reaching the KARMEN detector, the exotic particle decays to a partially electromagnetic state, such as $e^+e^-\nu$ or $\gamma\nu$. The $e^+e^-\nu$ decay is strongly favored by recent KARMEN data [2]. This slow moving exotic particle (hereafter denoted as Q^0) would have a mass of 33.9 MeV/c^2, which is near the kinematic threshold for $\pi \rightarrow \mu Q^0$ decay. Proposed explanations for the timing anomaly include heavy sterile neutrinos [3,4] and light neutralinos [5].

The KARMEN experiment reports a signal curve for pion branching ratio $B(\pi \rightarrow \mu + Q^0)B(Q^0 \rightarrow \text{visible})$ versus lifetime. Their signal region extends as low as 10^{-16} for a lifetime of 3.6 μs. For branching ratios above this minimum, there exist two solutions to the KARMEN anomaly (at small and large lifetimes). Certain portions of the KARMEN signal have already been excluded. Experiments at the Paul Scherrer Institute (PSI) [6,7] have performed searches for this exotic particle by studying the momentum spectrum of muons and electrons produced by π^+ decays in flight. PSI has excluded any exotic pion decays to muons with branching ratios above 2.1×10^{-8} at 90% C.L., and to electrons with branching ratios above 0.9×10^{-6} at 90% C.L. In addition, there exist astrophysical constraints on certain decay modes of the Q^0 which exclude lifetimes above 10^3 s. Despite the above limits, portions of the KARMEN allowed signal region remain to be addressed.

The E815 (NuTeV) neutrino experiment at Fermilab has performed a direct search for the Q^0 decay by combining the capabilities of a high intensity neutrino beam with an instrumented decay region (the "decay channel"). During the 1996–1997 fixed target run at Fermilab, NuTeV received 2.54×10^{18} 800 GeV protons striking a BeO target with the detector configured for this search. The secondary pions and kaons produced from the interaction were subsequently sign selected using a series of magnets and focused down a beam line at a 7.8 mrad angle from the primary proton beam direction. The pions and kaons could then decay in a 440 m pipe before hitting a beam dump. A total of $(1.4 \pm 0.1) \times 10^{15}$ pion decays and $(3.6 \pm 0.4) \times 10^{14}$ kaon decays occurred in the pipe. The neutral weakly interacting decay products (neutrinos and possibly Q^0's) traveled through approximately 900 m of earth berm shielding before arriving at the decay channel.

The instrumented decay channel (Fig. 1) consisted of a series of helium bags, extending a total of 34 m in length, interspersed with 3 m $\times$ 3 m multiwire argon-ethane drift chambers. The drift chambers were designed to track charged particles from decays occurring within the helium. Upstream of the decay channel stood a 4.6 m $\times$ 4.6 m array of scintillation plates, known as the veto wall, used to detect any charged particles entering from upstream of the detector. Downstream of the decay channel was the

7.8 E872 - MEASUREMENT OF τ PRODUCTION FROM THE PROCESS $\nu_\tau + N \rightarrow \tau$

Aichi (Japan), Athens (Greece), UC/Davis, Changwon Nat'l (Korea), Coll. de France (France), Fermilab, Gyeongsang (Korea), Kansas State, Kobe (Japan), Kon-kuk (Korea), Korean Nat'l (Korea), Minnesota, Nagoya (Japan), Osaka Sci. Ed. Inst. (Japan), Pittsburgh, South Carolina, Toho (Japan), Tufts, Utsunomiya (Japan)

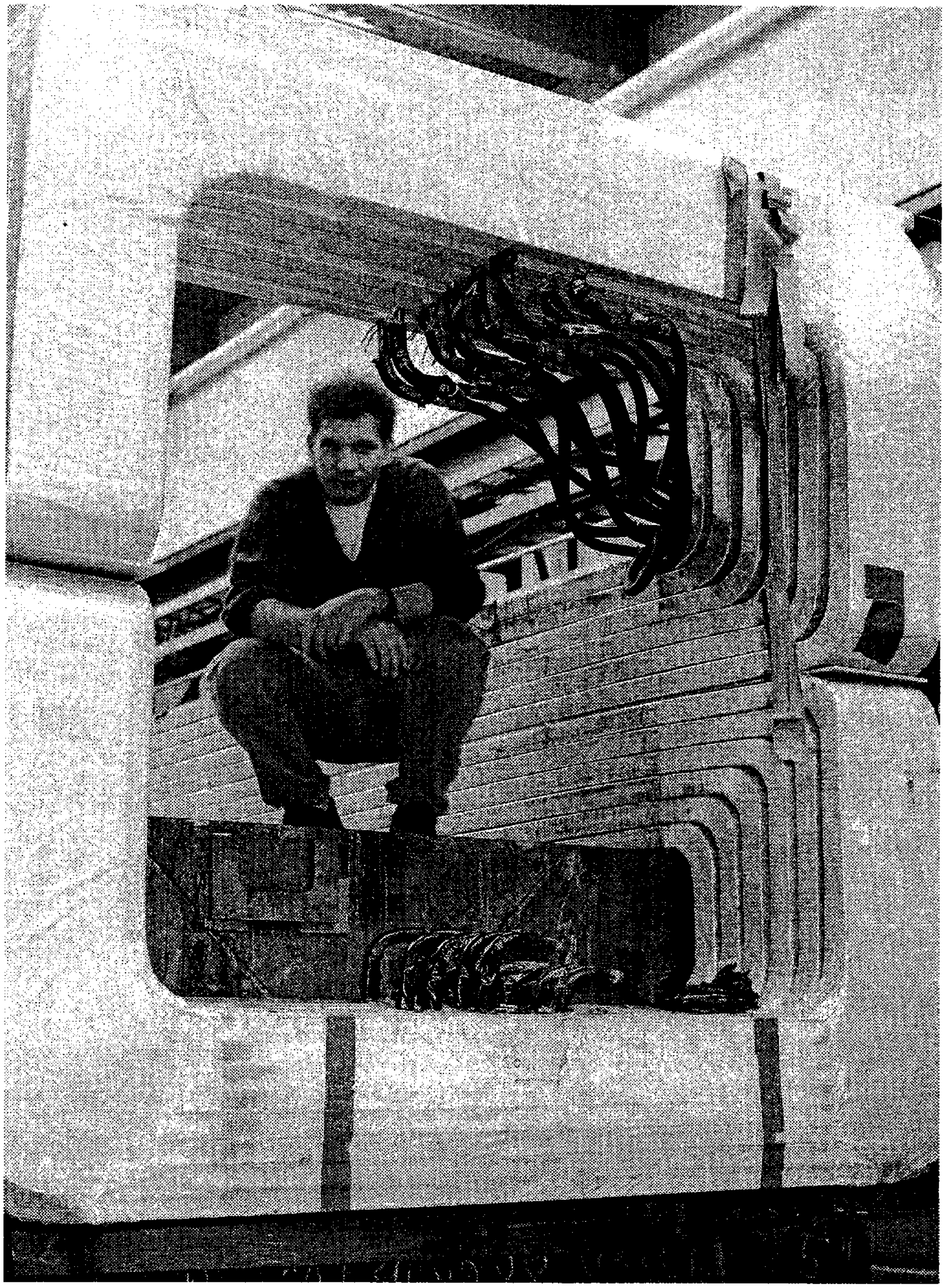
This experiment was designed with one main objective: to recognize and analyze τ neutrino interactions for the first time.

Neutrinos are very low-mass or zero-mass, chargeless fermions. The first to be seen was associated with the electron. Soon another electron-like particle, another lepton, was found. It was called the "muon," and it too had a distinct neutrino partner. After the third lepton, the tau, was discovered, it was expected that its neutrino partner, the τ neutrino, must exist.

There are several reasons why the τ neutrino had not been observed in the same manner as the electron and muon neutrinos. First, although electron neutrinos are extremely common particles (they are radiated by the sun and by nuclear reactors), it is much more difficult to produce suitable τ neutrinos at a laboratory. Secondly, only one τ neutrino out of 10^{14} will interact with ordinary matter, so one needs to produce a very large number of neutrinos. Third, the interaction can be identified as coming from a τ neutrino only if the detector spatial resolutions are very good, down to 1/1000 of a millimeter.

In the DONUT experiment, the τ neutrinos interact in 260 kilogram stacks of nuclear emulsion, much like photographic film, so that a very detailed microscopic record of each interaction is made. These emulsions are analyzed not by eye, but by digitizing cameras that record the tracks emerging from the interaction as computer files for study later. The experiment has been searching the emulsion data for 2 years, and we have several events that are most likely from tau neutrinos, but an additional set of data is being examined to confirm this. About 20 τ neutrino interactions should be in this data set.

Experimental neutrino physics is a difficult endeavor, requiring a lot of technology and resources, which only a laboratory like Fermilab can provide. It is no surprise that we have had to wait as many years after the tau lepton was seen (1976), as it took to see the first neutrino (1956) after it was hypothesized (1933).



E872 Degree Recipients

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N. Itoh	M.S.	Nagoya University

E872 Conference Proceedings

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Nuclear Physics B (Proc. Suppl.) 77 (1999) 259–264

NUCLEAR PHYSICS B
PROCEEDINGS
SUPPLEMENTS

Result from DONUT -Direct Observation of ν_τ interaction-

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Current status of DONUT(FNAL/E872) is reported. We have exposed emulsion target in '97 fixed target run and accumulated neutrino events corresponding to the total proton exposure of $\sim 4.55 \times 10^{17}$ 800GeV protons and the target weight of $\sim 250kg$.

In the preliminary analysis, we have located 34 neutrino interactions in Emulsion target and found one event which can be explained as $\nu_\tau(\overline{\nu_\tau}) + N \rightarrow \tau^-(\tau^+) + X$ followed by $\tau^- \rightarrow e^- + \nu_\tau + \overline{\nu_e}$ or $\tau^+ \rightarrow e^+ + \nu_e + \overline{\nu_\tau}$.

1. Introduction

DONUT(Fermilab E872) is a beam dump experiment which intend to observe tau neutrino charge current interactions for the first time in the world.

In this experiment, a prompt neutrino beam containing ν_τ was created by dumping 800GeV protons on tungsten beam dump. The source of ν_τ and $\overline{\nu_\tau}$ is the cascade decay of $Ds^-(Ds^+) \rightarrow \tau^-(\tau^+) + \overline{\nu_\tau}(\nu_\tau)$ followed by $\tau^-(\tau^+) \rightarrow \nu_\tau(\overline{\nu_\tau}) + X$. The ratio of ν_τ charge current interactions is safely expected to be $\sim 5\%$ due to reliable measurements of the branching ratio of $Ds^- \rightarrow \mu^- + \overline{\nu_\mu}$ in the previous experiments using hybrid emulsion detector [1,2].

The method to detect ν_τ CC interaction is the topological detection of the decay of the emerging τ from the CC interaction. For this purpose, nuclear emulsion was utilized as a target and a tracking device. Nuclear emulsion has three dimensional resolution of $\sim 1\mu m$ and is especially suited to the detection of short decay path of the τ. Same kind targets were used in CHORUS of which purpose is to detect the oscillation from ν_μ to ν_τ [3].

In the next section, DONUT experimental set up including the prompt neutrino beam line will be described. In the following section, the status of '97 exposure and the current status of the emulsion analysis will be reported.

2. Prompt Neutrino Beam Line

The preparation of prompt neutrino beam line which is suited to the emulsion exposure was one of the key of this experiment.

The expected most serious problem was the high density penetrative muon flux from the beam dump target (μ from charm semileptonic decay etc.) In order to sweep out them from the beam line, two magnets are installed at the downstream of the dump target (tungsten: 40inch long). The maximum Pt kick of the first magnet is 8 GeV. Adding to them, passive shields made of steel and lead were set in front of the emulsion target in order to stop low energy components, like scattered muon and electromagnetic components from muon bremstralung. At the position of 36m downstream from the dump, background free zone of $\sim 1m$ width was kept and at where the emulsion target was installed. Fig.1 shows a schematic view of the beam line.

When we received the first beam on the dump target at Oct.'96, we observed a lot of low energy γ ray backgrounds from nuclear captures of thermalized neutron and activated gas components which we did not expect. We modified the shields around beam dump, added extra γ shields around the emulsion target and succeded to supress the background level below allowed level for emulsion exposure at the end May '97.

0920-5632/99/$ – see front matter
PII S0920-5632(99)00425-9

Technological Developments
SECTION 8

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8. TECHNOLOGICAL DEVELOPMENTS

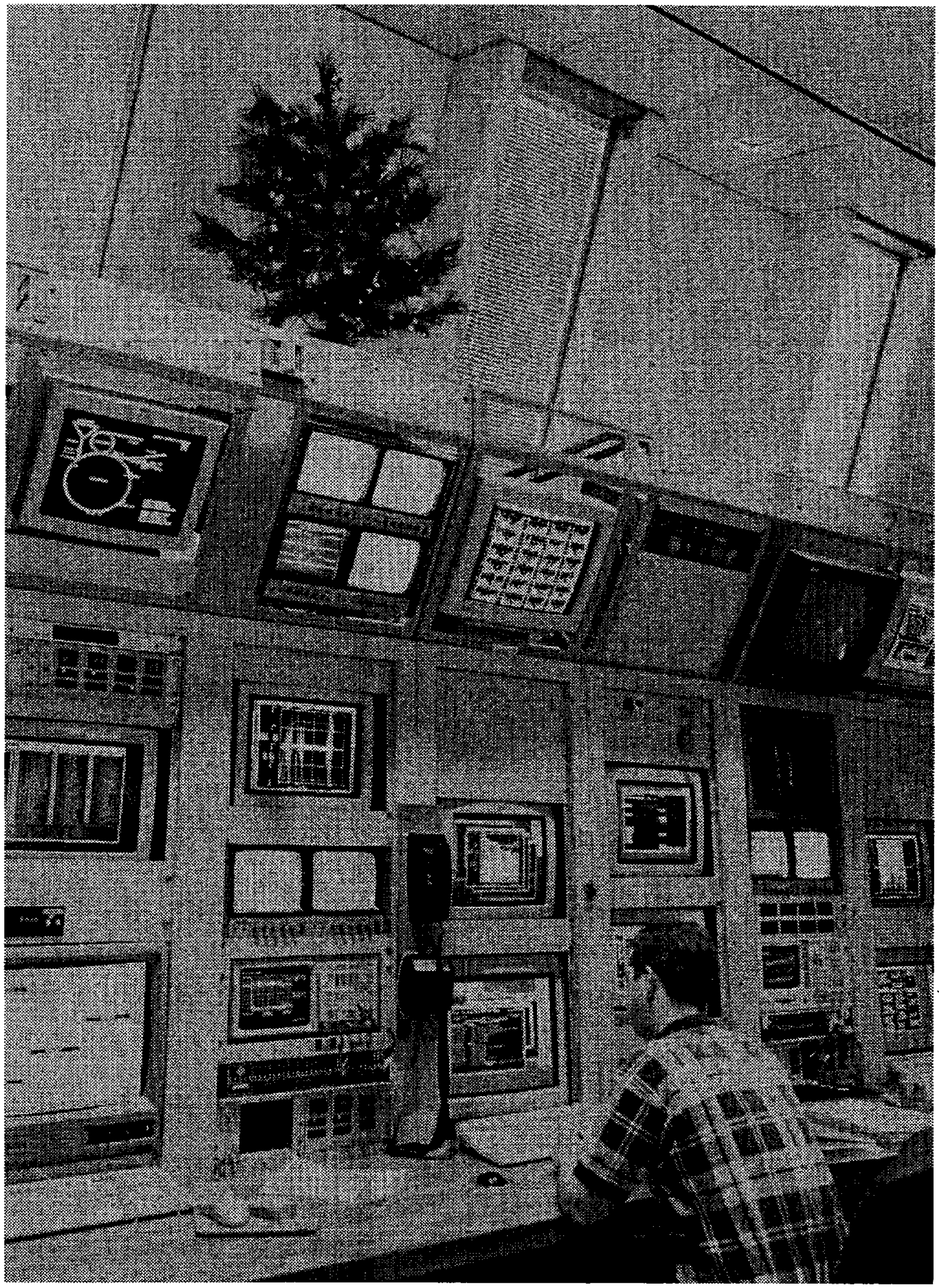
8.1 INTRODUCTION

The physics produced by the Tevatron fixed target program depended on a whole sequence of technological developments in accelerators, detectors, and computing. Many experiments required one or more of these innovations to even be feasible in the first place, and to achieve their goals. The experimental collaborations themselves contributed significant advances in the technologies required. These advances have had far-reaching impact on subsequent work, both here at Fermilab and elsewhere in the world. Some of these advances transcend in importance the experiments for which they were developed. In this section we will hit a few of the highlights in this area. Where possible, we have tried to include a reference to each of these works.

8.2 ACCELERATOR AND BEAM LINES

By far the most impressive, important, and obvious technical development is the Tevatron itself. From the experimentalist's viewpoint, it not only provided twice the beam energy but also a much longer spill. The spill duty factor was increased from 1 second of beam every 15 second to 20 seconds of beam every 60 seconds; a factor of five improvement over the Main Ring. The longer spill length required several important innovations in the Tevatron itself. An extraction system, generically known as QXR, was extensively modified based upon microprocessor technology to handle the much longer beam spill.

The external beamlines required significant new developments as well. The longer spill implied much less intensity per second in the external beamlines. A new beam position monitoring system was developed to sense and control the external beams. These beams are as much as one million times less intense than the circulating beam in the Tevatron itself. The higher energy beam required twice the bending power in existing tunnels, which were originally designed for 200 GeV beams. The new requirement was to deliver the extracted 800 GeV protons to the Meson, Proton, and Muon Laboratories. This led to the development of the strings of superconducting magnets and their associated cryogenic plants, known as the left, right and muon bends. Many will remember channel 13 messages like "LEFT BEND QUENCH – NO ESTIMATE" - these things were far from trivial.



The higher beam energy and the sensitivity of the downstream cryogenic magnet strings required significant upgrades to the stations that split the extracted proton beams to each of the

Proton, Neutrino, Muon, and Meson Laboratories. Motion controls and new pulsed magnets were installed to move the fast spill around the septa without burning them up, and the septa themselves were improved.

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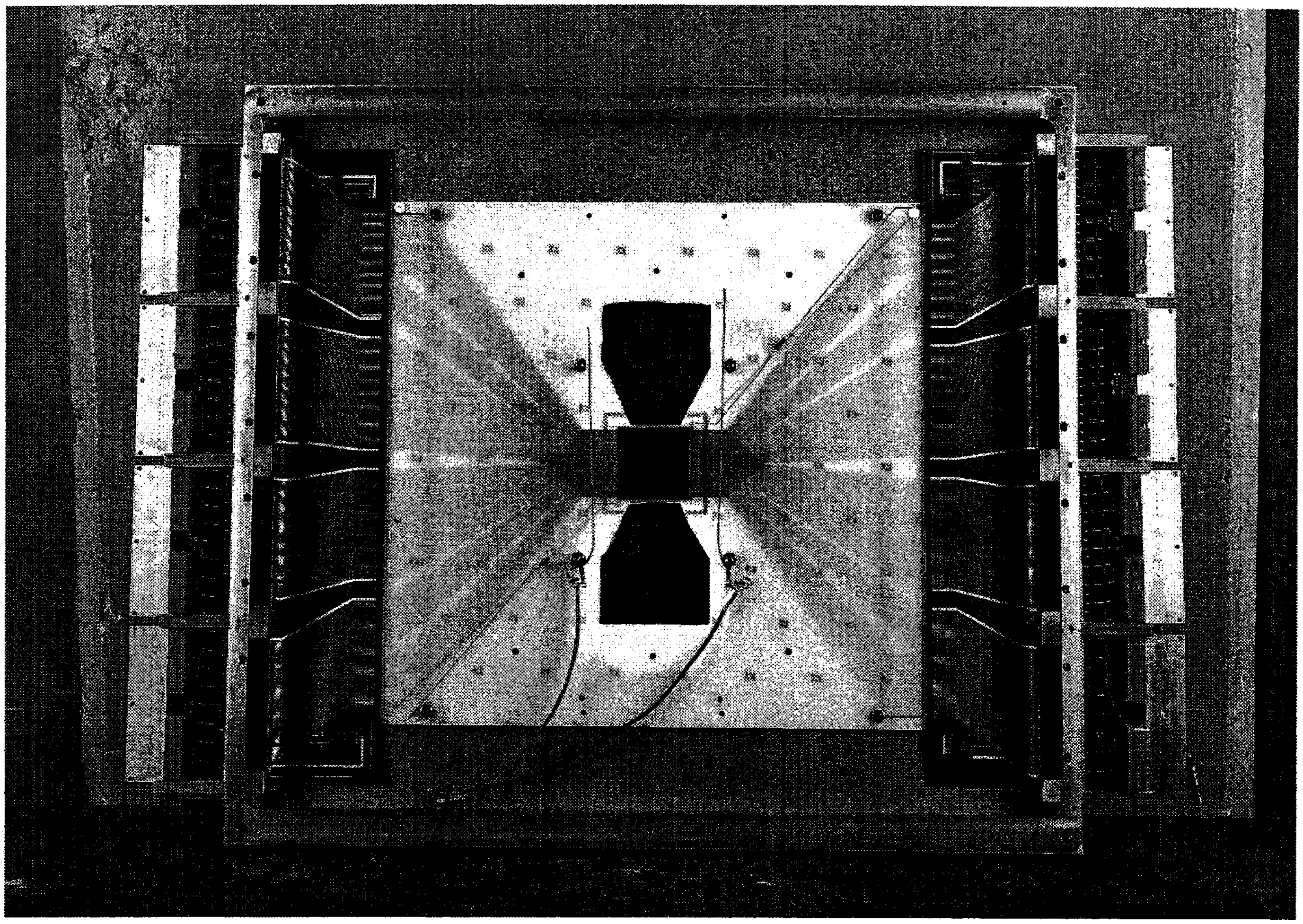
8.3 DETECTORS

The most notable and noted advance in detector technology was the development of the silicon microvertex detectors by the Santa Barbara group for the charm photoproduction experiment E691. This development, built on the detector development work of European groups working at CERN, revolutionized heavy quark physics. This occurred first in charm production, and latter in studies of hadrons with beauty in both fixed target and collider experiments, as well as in the discovery of the top quark in the Tevatron collider . This development received significant recognition with the 1990 award of the Panofsky Prize to Mike Witherell for the advances in charm physics that it made possible.

The group from the Petersburg (then Leningrad) Nuclear Physics Institute made a major advance in precision electron identification with their development of a large transition radiation dectector (TRD) system for the precision Σ^- beta decay experiment E715. This large system achieved electron/pion separation of several thousand, with an electron inefficiency of less than 1%. These techniques have been used and further extended at Fermilab in experiments E761, E781, and E799.

The KTeV experiment developed a CsI photon calorimeter with outstanding energy and position resolution, excellent linearity, and very high rate capabilities. They achieved better than 0.75 % energy resolution over virtually their entire photon energy range of 5-100 GeV. They developed a new digital readout system with 17 bits of dynamic range housed in the photomultiplier base of each of their 3100 CsI crystals.



The heart of The KTeV CsI readout was an application specific integrated circuit (ASIC) called the QIE chip, one of several ASIC's developed on the 14^{th} floor of Wilson Hall for use in the Tevatron fixed target program. Others included silicon microstrip and wire chamber electronic circuits. These chips, and the ability to develop new circuits in the latest technologies, have come into widespread use since these early efforts.

The technique of recording the position of Cerenkov photons at the focal plane of a large Cerenkov detector for particle identification over a broad angular range (the Ring Imaging Cerenkov Counter, RICH) was pioneered by the E605 experiment. A Fermilab group lead the effort in SELEX (E781) to develop a large ring imaging Cerenkov counter (RICH) based upon 2848 small phototubes as the photodetector. The SELEX RICH achieved useful π-K separation in full multi-hadronic events up to 165 GeV/c with 12 photons observed on a typical ring. The new CKM experiment planned for the Main Injector fixed target program is based, in part, on this detector technique that accommodates very high beam rates with excellent time resolution.

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8.4 COMPUTING

The use of "farms" of parallel computers bases upon commercially available processors is largely an invention of the Fermilab Advanced Compter Project (ACP). This technique has become widespread, both for on- and off-line computing - for selecting, acquiring, and processing the vast volumes of data that come with a full hardronic cross-section.

The original ACP I computer was developed at Fermilab in the mid 1980's based on a Motorla 68020 processor and an ACP designed bus structure which allowed dozens of processors to analyze individual events in parallel. Much of the data from the early Tevatron fixed target runs were reconstructed off-line on farms of ACP I processors in the Feynman Computing Center. At its peak, we had 400 processors in use.

This technique was extended in the next generation to farms to the use of commercial UNIX workstations. Farms like these have been established in the Feynman Computing Center as well as collaborating universities and national laboratories. For example the 50 terabytes of data colleted by experiment E791 was reconstructed in parallel on farms at Fermilab, the University of Mississippi, Kansas State University and the CPBF in Rio de Janeiro.

This is an innovation which has become an industry standard in our field. Now there is hardly an experiment that does not have both an on-line computing farm for sophisticated software trigger decisions and an off-line farm for rapid parallel reconstruction of events.

As the Tagged Photon Laboratory charm group moved from experiment E769 to experiment E791, they pioneered the use of 8 mm magnetic tape for online data recording. As the *before* and *after* pictures from E769 and E791 show, they had good reason to do so. The change to a new recording medium was adopted as a new standard by the Computing Division (then the Computing Department in the Research Division). After considerable work (and pain), it became the de facto standard for data recording, both at Fermilab and in many other places in particle physics.

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APPENDICES
SECTION 9
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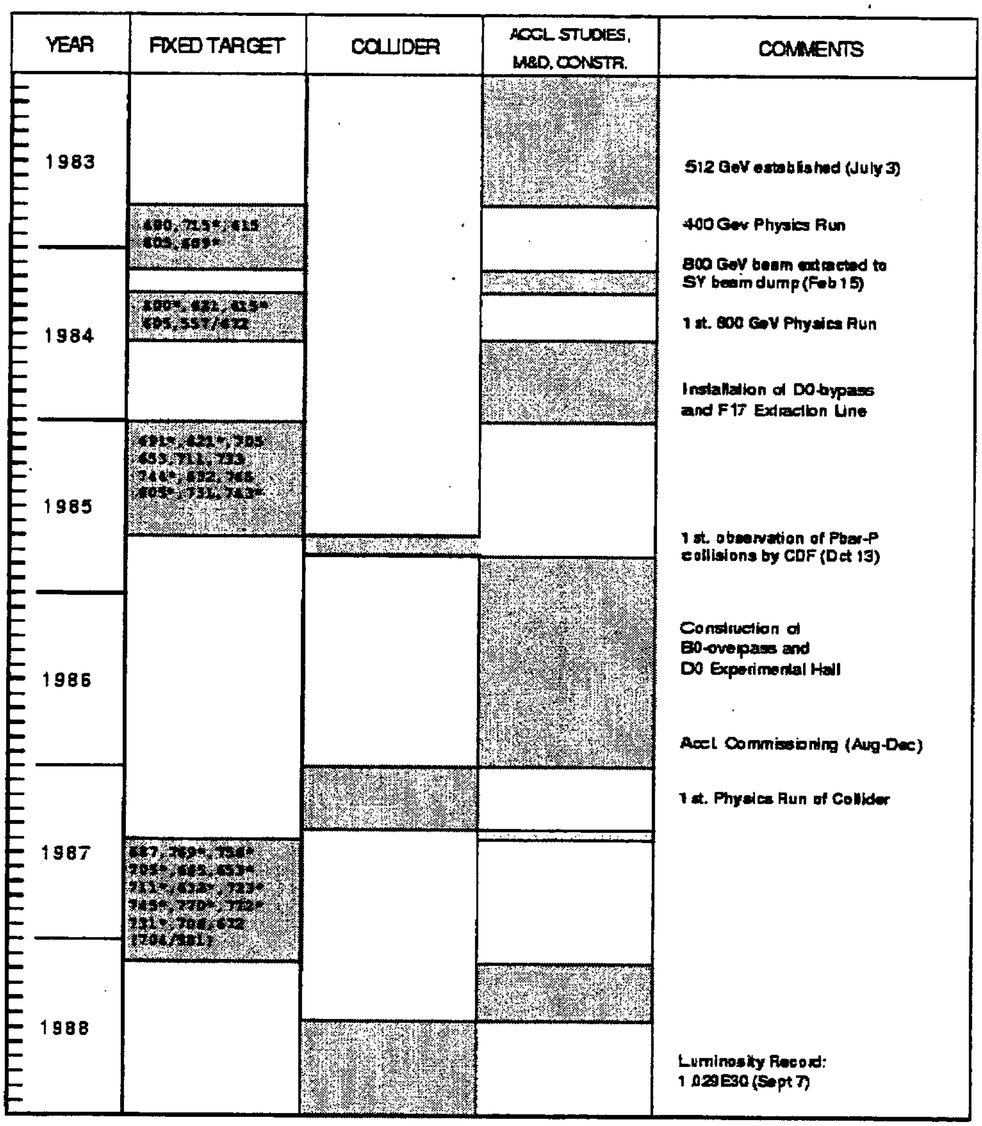
9.1 HISTORY

APPENDIX 1

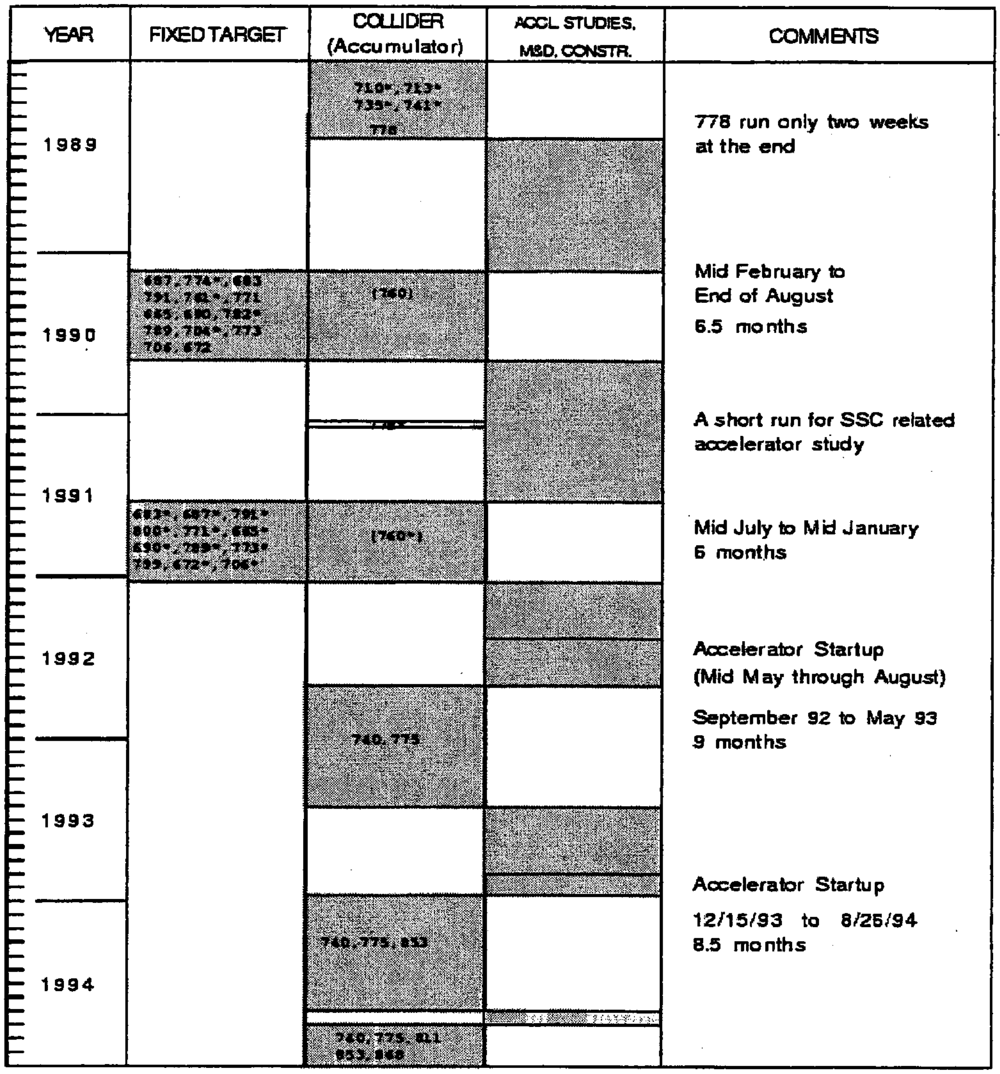
HISTORY OF TEVATRON OPERATION

1983 - 1988



HISTORY OF TEVATRON OPERATION

1989 - 1994



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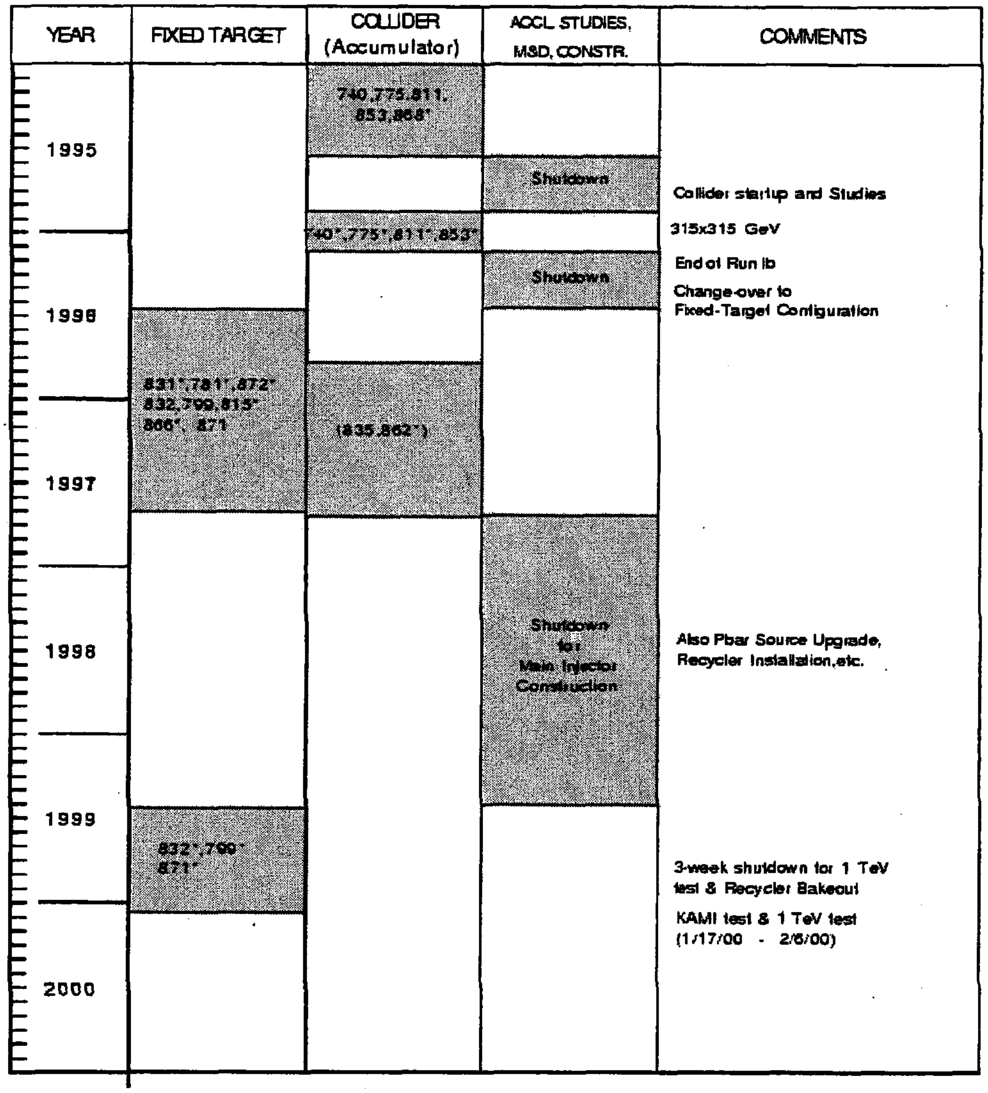
HISTORY OF TEVATRON OPERATION 1995 - 2000



* Completed

9.2 DEGREE LIST

APPENDIX 2

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Gavin Reed Blackett	University of Tennessee	Ph.D.	E687
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Gianluigi Boca	Florida State University	Ph.D.	E711
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Germano Bonomi	University of Pavia	Ph.D.	E687
Germano Bonomi	University of Pavia	Laurea	E771
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F. Bossi	University of Pavia	Ph.D.	E400

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Y.C. Chen	National Cheng-Kun University	Ph.D.	E789
Byungu Cheon	Korea University	Ph.D.	E687
I. Chini	University of Milano	Ph.D.	E687
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Paul Draper	Indiana University	Ph.D.	E672
Tim Dubbs	University of Iowa	Ph.D.	E761
Jean Etienne Duboscq	University of California at Santa Barbara	Ph.D.	E691
James M. Dunlea	Ohio State University	Ph.D.	E653
Casey Durandet	University of Wisconsin	Ph.D.	E771
Emrullah Durucan	Max-Planck-Institut Fur Kernphysik	M.S.	E781
Jeffrey Walton Duryea	University of Minnesota	Ph.D.	E756
Sajan Easo	Pennsylvania State University	Ph.D.	E706
K. Ebara	Utsunomiya University	M.E.	E653
U. Ecker	Wuppertal University	Ph.D.	E665
Valerio Elia	University of Lecce	Laurea	E771
Janice Enagonio	University of Colorado	Ph.D.	E400
M. Erdmann	University of Freiberg	Ph.D.	E665
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