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DOE/ER/40842--T2

CHARM DECAYS and HIGH ENERGY PHOTOPRODUCTION

DOE GRANT NO. DE-FG05-94ER40842

FINAL REPORT
April 1994 - May 1997

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TABLE OF CONTENTS

A. SUMMARY	1
B. FERMILAB EXPERIMENTS E687 AND E831	1
B.1. Experimental Approach	2
C. UPR CONTRIBUTIONS TO E687 AND E831	5
C.1. Summary of Accomplishments	5
C.2. Details of Accomplishments	6
REFERENCES	11

A. SUMMARY

This project involved continued participation by the Physics Department at the Mayaguez Campus of the University of Puerto Rico (UPR) in high energy physics experiments carried out at Fermilab. The UPR is a member of the E831 collaboration which includes Fermilab and leading U.S., Italian, Brazilian and Korean universities. E831 is an upgrade to the E687 spectrometer with the goal of a tenfold increase in the statistics for the study of the photoproduction and decay of charmed particles. This spectrometer has been significantly upgraded to maintain and expand its capabilities even at considerably higher beam intensities.

E687 completed its last data run in January 1992. Approximately 100,000 charm events were fully reconstructed from this data and results of the analysis have appeared in several publications.[3-36]. The UPR has been participating in E687 since 1985 when the experiment was in its early stages of construction. A grant from the DOE Division of High Energy Physics (starting in April 1994) and another from the DOE EPSCoR Program (starting in October 1994) allowed a considerable increase in the activities of the UPR group. Given the group's capable performance, the responsibilities assigned to it by the collaboration have increased to the point where they now include four major detectors in E831. All four detectors were ready on time for the start of the E831 run in July 1996. This is a remarkable performance if one considers that there is only one senior member in the group and that the students are all MS or undergraduate students. The group has also been active in the development of simulation, data acquisition and analysis software.

B. FERMILAB EXPERIMENTS E687 AND E831

The general goal of E687 and E831 is the study of the production and decay of heavy-flavor particles using a high intensity, high-energy photon beam. The interest in such experiments is manifold. The heavy quarks belong to the higher families in the standard model and their study can shed light on the question of whether the family structure of the standard model is correct in all of its implications. Also, standard model (QCD) predictions (based on low-order perturbation theory) for processes involving the color interaction should be better approximations to reality for the heavy quarks than for the light quarks allowing, in principle, more stringent tests of the standard model. With respect to the choice of the production mechanism, in comparing photoproduction to hadroproduction, photoproduction offers the advantage of a higher ratio of heavy-quark to light-quark production and thus a better "signal-to-noise" ratio.

One of the areas of interest of the UPR group is the elastic and inelastic production of closed charm states, the J/ψ and ψ' . It has been measured that gluons carry about 50% of the momentum of nucleons. It is essential for many aspects of the QCD that we know the energy-momentum distribution of the gluons in nucleons. Directly measuring the gluon distribution function of nucleons is difficult because it is hard to separate the contribution from gluons and from quarks experimentally. The inelastic photoproduction of the J/ψ provides a way to directly measure the gluon distribution function of the nucleon, $g(x_g = e_g/e_N)$, because its cross section is directly related to the gluon structure function.

B.1. Experimental Approach

A detailed description of the E687 beam and spectrometer can be found elsewhere.[1,2] Only a brief description will be given here. The two-magnet spectrometer (Fig. 1) identified charged and neutral hadrons, muons, electrons and photons. Charged particle tracking was accomplished by a silicon microstrip detector with 8400 strips and a proportional chamber system with 13400 wires. Three multi-celled Cerenkov counters provided charged particle identification. Neutral vees were reconstructed over a decay path of about 10 meters. Photons and electrons were detected by two lead/scintillator arrays, one at the center of the aperture and one at large angles. Muons were detected over the full aperture by scintillation hodoscopes and proportional tubes inserted behind steel hadron filters. A gas hadron calorimeter was used in the second-level trigger to reject purely electromagnetic events. This complement of detectors allowed the observation of a wide variety of charmed baryon and meson decay modes. In particular, the microstrip system separated tracks coming from the downstream decays of charmed and beauty particles from those coming from the primary production vertex.

Figure 1. E687 Spectrometer.

The main goal of E831 is a tenfold increase in the number of charm events detected by an upgraded E687 spectrometer. This increase comes from a factor of five increase in the beam flux and a factor of two improvement in efficiency. The increase in flux is due mainly to a change to liquid deuterium in the production target and the addition of a positron arm to the beam line (both of which had already been implemented and tested during the 1991 run). Additional increments are a result of an increased primary proton flux, a decreased electron beam energy and other changes to the production target. E687's photon beam was created via the bremsstrahlung process from an electron beam (average energy 350 GeV) with a wide energy spread ($\pm 15\%$). This beam struck a lead (Pb) radiator (20% of a radiation length) to create the photon beam.

Figure 2. E831 Spectrometer Layout

which had a similar energy spread around an average energy of 200 GeV. E831's beam is currently produced the same way as E687's except for three differences: (1) a positron component has been added to the beam incident on the radiator, (2) the incident electron-positron energy has been reduced to 250 GeV and (3) the primary proton flux (from which the secondary e^+e^- beam is derived) has been increased by a factor of two.

The reason for the changes is to increase the detected charm yields. The reduction in energy, although accompanied by a lower charm production cross-section, actually increases yields due to an associated increase in the geometrical acceptance for charm events. This reduced energy is also made necessary by the presence of the positron component which would have an unacceptably high proton contamination if the energy were not reduced. Fermilab's total proton flux has not increased since E687 and the increase in the fraction allotted to E831 comes at the expense of other concurrent experiments making it more vulnerable to fluctuations in the accelerator's flux.

The upgrades to the detectors for E831 (Fig. 2) were directed mainly toward improving their capacity to handle the large increase in flux. Some detectors required only minor modifications but most underwent significant changes. Among these are the muon system, the hadron calorimeter, the inner electromagnetic calorimeter and the tracking system. The triggering strategy was changed to incorporate a new hadron calorimeter (scintillating tile design) in the first-level. The time response of the vertex microstrip detector and the muon system were

significantly improved. A straw tube tracking system now covers the beam region of the PWCs. The inner electromagnetic calorimeter was changed to a lead-glass array and the data acquisition system was completely rebuilt to handle the higher rates.

Major changes were implemented in the experimental target. Most of the data from E687 was obtained with a one-piece 4cm-long Be target. E831 uses a segmented target of the same total length in order to increase the percentage of charm decay vertices occurring outside the target material. This has been proven to significantly reduce backgrounds from secondary interactions in the target material. Another important change in the target area is the addition of silicon planes interleaved with the target pieces. Monte Carlo simulation predicts that vertex longitudinal position resolution will be improved by at least 30% due to the additional planes.

C. UPR CONTRIBUTIONS TO E687 AND E831

C.1. Summary of Accomplishments

The major accomplishments during the grant period (April 94 - May 97) were:

- ▶ Design, construction, installation and commissioning of a muon detector for E831.
- ▶ Design, implementation and commissioning of a first level inner muon trigger for E831.
- ▶ Refurbishing and recommissioning of two Cerenkov counters, major detectors in E831.
- ▶ Significant participation in monitoring E831 data acquisition.
- ▶ Development of an improved algorithm for muon identification in E687/E831.
- ▶ Separation of an enriched subsample of J/Ψ events in E831.
- ▶ Preliminary analysis of inelastic J/Ψ production in E687.
- ▶ Participation in the development of a simulation program for E831.
- ▶ Participation in the construction of the new E831 hadron calorimeter.
- ▶ Participation in the installation of the E831 data acquisition system.

Our major goals and objectives have been achieved. In fact, our contributions to E831 have been much more substantial than we had anticipated in our 1993 proposal. During this period the UPR group has moved from a situation of almost nonexistent infrastructure to a situation where the group has become a major contributor to the experiment.

The first year was a building year where the necessary infrastructure was put in place and graduate and undergraduate students were trained. However, at the same time, work on the stated objectives was begun and all commitments were met. By September 1995, our newly built MH3 muon detector was one of the first new detectors for E831 to arrive on the experimental floor. We had also made contributions to the construction/installation of other detectors. The group was ready to undertake additional projects.

The grant's second year was marked by a significant increase in the responsibilities assigned to our group. The number of major detectors under our responsibility increased from one to four. Our interest in muon physics led us to undertake the design and implementation of a first-level inner muon trigger and the refurbishing of the existing muon trigger counters. The recommissioning of two Cerenkov counters (C2 and C3) also became major projects since they required the installation of new ADCs and the addition of new TDCs, besides the recalibration of all phototubes. We took the opportunity to install LED light sources inside the counters to be used in determining the optimum high voltage setting for each channel (210 in total).

For E831 the major event during the grant period was the start of data acquisition in July 1996. Our muon detector was one of the first new detectors to become operational and all our detectors were ready when the beam arrived. After adjusting timing and high voltage, the group has been contributing significantly to the continuous monitoring of the data acquisition.

Although our main focus during these three years has been on hardware development as was dictated by the imminent arrival of E831 beam, we have not neglected the development of software both for E687 analysis as well as for E831 simulation and analysis. Software was developed both to identify inelastic J/Ψ events in E687 data as well as to simulate such events. This software can also be used for E831. The same can be said for the new algorithm for muon identification we developed which minimizes misidentification of pions as muons. Major contributions have been made to the simulation of the inner muon system in E831 as well as to the development of routines related to the adjustment/calibration of the E831 muon and Cerenkov detectors.

C.2. Details of Accomplishments

Our first E831 hardware responsibility concerns what we call the "inner" muon system which covers the central 40 mrad of our spectrometer. The E687 inner muon system consisted of 4 arrays of muon proportional tubes interspersed with coarse-granularity, triggering, scintillator arrays and hadronic filter steel. Our plans for the E831 muon detector changed somewhat since our original proposal. The proportional tubes were replaced with two scintillator counter hodoscopes (MH2 and MH3) in positions as well-filtered as the tubes. This allows us to latch muon hits within one or two 20 ns spaced RF buckets, whereas the proportional tube arrays required a microsecond gate. We thus can greatly reduce the false identification due to the muon halo. The system also includes an additional upstream array (MH1) in a somewhat less protected position but with the advantage of reduced multiple scattering effects allowing an improvement in track matching which will considerably reduce backgrounds to charm semileptonic and fully leptonic decays. The MH2 and MH3 arrays are necessary to provide a performance (at least) equivalent to E687 but at the higher beam rate of E831. The MH1 array is an attempt to provide a muon system of improved performance in E831.

We were responsible for the design, construction, installation and commissioning of MH3. MH3 consists of 108 counters each 10 cm wide, 1.5 cm thick and (most of them) 115 cm long. They are arranged in two (U and V) stereo planes with their lengths aligned at 30° with respect to the X direction of the MH1 and MH2 arrays (Fig. 3). The stereo angle significantly reduces our susceptibility to track matching confusion which will be larger in the higher-rate environment of E831 vs E687. The aperture filled by the arrays, however, has vertical and horizontal sides. In order to fill most of the aperture, some counters had odd lengths. An important aspect of the design is that the detector dimensions were chosen so that the array is highly symmetric. The symmetry built into the design permitted the odd-size counters to be built in groups of four, thus reducing the complexity of construction.

BICRON BC-412 scintillator and 40 mm diameter, EMI 9902 phototubes were used to build the counters. Most of the phototubes and corresponding bases were recovered from the old E687 inner electron calorimeter which is being replaced by a lead-glass array. This reduced a major element in the cost of MH3.

The MH3 frames were designed by us and built by Fermilab. Actually two frames were built but the symmetry of the MH3 design is such that the frames are nearly identical thus simplifying construction. To achieve the independent stereo views, one frame is placed rotated 180° through a vertical axis with respect to the other. The counters are held in place by clamps specifically built for this purpose. Precise alignment of the counters is assured by the precise machining of the holes for the clamp alignment pins and fastening screws.

Figure 3 MH 3 inner muon detector (one of two planes). The view is along the beam direction.

Each MH3 counter was individually tested and plateaued using cosmic rays before being mounted. With beam it was possible to determine and adjust the timing of the signals from each counter. The software to unpack the muon data block and make it accessible to the online data monitoring was developed by our group. A visual display of the MH3 counters struck during any given event was one of the first solid pieces of evidence that E831 was a working experiment (at

least in a basic way). Our preliminary analysis of E831 calibration data indicates that the MH3 hodoscopes are at least 98% efficient.

One of the areas in which E831 differs from E687 is the first level trigger. In E687, the dimuon trigger was at the second-level. In order to be able to take data at a higher beam intensity, we needed to reduce the output rate of the first-level trigger in E831. The hadronic energy trigger was brought to the first level for this purpose. If dimuon triggers were brought in at the second level, there would be an unnecessary hadronic energy threshold for each dimuon event, lowering efficiency and making analysis very difficult. The same is true for single muon triggers such as a semimuonic trigger which were not used in E687 but are of primary importance in E831.

Our interest in muon physics led us to undertake the design and implementation of a first-level muon trigger. Our proposed trigger scheme was presented to and accepted by the collaboration at a meeting in January 1996. The scheme divides the existing (E687) IM trigger counters into four quadrants geometrically. Each quadrant consists of 3 planes of scintillators in coincidence. The trigger logic uses LeCroy NIM modules and a logic module of the same design as that used in the part of the first level trigger that incorporates the HxV scintillation counters. The trigger logic sends out a single-muon signal when at least one quadrant has a coincidence, and a dimuon signal when at least two quadrants have coincidences. The design was based on studies using E687 calibration data and Monte Carlo simulation to estimate the acceptance and trigger rates for various schemes. A crucial aspect of the design is the use of high speed cables to meet the timing requirements. Their high cost, in turn, forced us to place the logic electronics as close as possible to the detector minimizing the number of long cables runs. As a natural part of this project we undertook responsibility for refurbishing the existing muon counters.

The IM trigger was one of the first triggers activated upon beam arrival. It was immensely useful in the commissioning of many detectors allowing calibration with minimum ionizing particles and the adjustment of the timing of channels with low flux.

E831 uses the same Cerenkov system as E687 which consists of three major counters. UPR is now responsible for two of these (C2 and C3) with a total of 210 channels. Besides repairing inoperative components, our group completely replaced the associated electronics with new ADCs and added TDCs to measure the signal timing for each channel. Both counters were opened and the mirror optics was found to be in good shape requiring only minor adjustments. The counter enclosures were checked for light and gas leaks which were repaired with the result that gas consumption decreased by 40% compared to E687. LED light sources were installed inside each counter and the high voltage for each channel was redetermined on the basis of the separation of the single-photoelectron signal peak from the ADC pedestal noise peak. Software developed by our group for this purpose was used for the adjustment of all the Cerenkov counters. Finally, when beam arrived the timing for each channel was determined and adjusted.

With respect to data analysis with a view to extracting the gluon structure function, we have observed more usable J/Ψ ($z < 0.9$) in E687 data than that found in the samples studied by the NMC[38] and EMC[39] collaborations. In E687/E831, we detect J/Ψ 's through their decay to $\mu^+\mu^-$ pairs. We selected J/Ψ candidates based on the dimuon trigger, muon identification and the invariant mass of the muon pairs (Figure 4). We have observed about 1,000 J/Ψ candidates and about half of these can be used to extract the gluon distribution as they are in the region of validity of the color-singlet model ($z < 0.9$).

We have also developed an inelastic J/Ψ event generator using the color-singlet model to generate the kinematic variables for J/Ψ and the JETSET for the gluon jet. We integrated the J/Ψ event generator with the E687 Monte Carlo package SROGUE. On a first look, the event generator seems to emulate the kinematic distributions well (Fig. 5 & 6).

Figure 4 Invariant mass distribution of $\mu^+\mu^-$ pairs. There are about 1,000 entries in the peak region. The selections were dimuon trigger, muon identification.

Figure 5 The squared J/Ψ transverse momentum, $(p_T)^2$, distribution. The background contribution under the J/Ψ peak is taken into account by the side-band subtraction. The crosses are data points. The solid histogram is from MC with an arbitrary scale.

Figure 6 Elasticity, z , distribution of J/Ψ candidates. The background contribution under the J/Ψ peak is taken into account by the side-band subtraction. The crosses are data points. The solid histogram is from MC with an arbitrary scale to guide eyes.

Another of our major contributions to E831 was the development of data analysis software. We developed routines to unpack the muon detector data and make it accessible to the

offline analysis package. Routines for E831 inner muon identification were written by and are being tested. They are based on a new algorithm for muon identification implemented and tested on E687 data. Based on the calculation of a chi-squared statistic and a corresponding confidence level for the hypothesis that a given track is a muon, this algorithm provides better background rejection than one based on the number of muon planes consistent with a track. We are presently making modifications to apply it in E831. Our results on E687 data indicate that it reduces the level of pion misidentification by 36% with a small drop in muon identification efficiency.

Another major project concerned the performance of the inner muon trigger and its use to gather a sample of J/Ψ s decaying to two muons. This trigger was built because of our initiative to study J/Ψ s, a piece of physics which would have been lost without it. It was a difficult project because this trigger was particularly sensitive to accelerator beam quality which was not always the best. In fact, our work with this trigger led the collaboration to become aware of beam quality issues which were brought to Fermilab's attention and which led to an improvement in beam quality with benefits for the whole experiment. Our aggressive effort in this project resulted in an improvement of a factor of four in the rate of J/Ψ events written to tape compared to the rate when the experiment first turned on. In order to get a head-start on the analysis of a real signal, we have separated a large sample of events (approximately 15000) containing J/Ψ s decaying to two muons. Approximately one-fourth of the raw data tapes have been passed through the selection process. It is the existence of the muon trigger which allowed us to do this separation.

The J/Ψ sample is allowing us to develop the details of J/Ψ analysis in E831 before the official output from the track reconstruction analysis is available. Figure 7 presents an invariant mass histogram where the signal is seen to be very clean. The signal is already ten times larger than that achieved in all of E687 which leads us to estimate that E831's dimuon data set is at least 40 times that of E687.

Figure 7. Dimuon invariant mass histogram with a very clean J/Ψ peak (approximately 15,000 J/Ψs) and a clear Ψ' peak.

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