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RICE

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E704: “Comparison of spin asymmetries and cross sections in π^0 production by 200 GeV polarized antiprotons and protons”, Phys Lett. B 261 (1991) 201.

E704: “First results for the two-spin parameter A_{LL} in π^0 production by 200 GeV polarized protons and antiprotons”, Phys. Lett. B 261 (1991) 197.

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E704: “Large x_F spin asymmetry in π^0 Production by 200 GeV Polarized Protons”, FNAL Preprint 91/13-E.

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1. Project Abstract and Overview

We report here on the enormous amount of progress that we made for the year beginning September 1, 1990 (the date of submission of our latest progress report) for DOE Contract No. DE-AS05-76ERO5096. An intense analysis effort on the data we obtained in a seven month run on E704 last year has produced a flood of new results on polarization effects in particle production at 200 GeV/c. We are fortunate to be able to report in detail on those results. Our other Fermilab experiment, E683 (photoproduction of jets) has been delayed an unbelievable amount of time by Fermilab schedule slippages. It was scheduled and ready for beam two years ago! As this report is being written, we have been running for two months and are expecting four more months of production data taking. In this report we show some of our preliminary results. In addition we are near the end of a six month run on our CERN experiment, NA47 (SMC) which will measure the spin dependent structure functions for the proton and neutron. It is with a sense of relief, mixed with pride, that we report that all the equipment which we constructed for that experiment is currently working as designed. The random coincidence of accelerator schedules has left us slightly dazed, but all experiments are getting done and analyzed in a timely fashion.

As members of the Solenoidal Detector Collaboration, we have been preparing for the only currently approved experiment at the SSC. Here we report on our scintillating fiber tracker design and simulation activities. In addition we report the results of our investigation of the detector response to heavy Z particles. Since our last report, we have joined the D0 collaboration with the primary aim of contributing to the D0 upgrade over the next few years. It is also important for us to gain experience in collider physics during the period leading up to the SDC turn-on.

As in recent years, the format we follow in the Progress Report is to provide a brief writeup on each individual project in the main body of the report. In the appendix we include copies of published papers and manuscripts which give much greater detail about the different projects. The aim is to concentrate on the physics goals, results, and their significance in the main body of the report.

2. TASKS A and C – Experimental High Energy Physics

A. FNAL E704 – Spin Effects at 200 GeV/c

This ambitious experiment set out to measure polarization observables in particle production by the highest energy polarized proton beam that has yet been realized. Although there were actually several other experiments done under the aegis of this experiment number, such as total cross section differences for polarized proton – polarized proton interactions, our primary interest and responsibility lay with the forward spectrometer measurements of analyzing power (A) and spin transfer (D_{NN}) using both polarized proton and polarized antiproton beams. We began taking data in February, 1990 and ended in August, 1990 using the apparatus schematically depicted in Fig. 1.

Fig. 1. A schematic plan view of the E704 forward spectrometer.

Rice was responsible for the debugging and operation of fifty-one tracking planes of chambers, four segmented hodoscopes, our 25-meter Cherenkov counter used in the charged π and Λ experiments, and our calorimeter used in the high- x_F π^0 measurements. Much of this equipment was constructed by the Trieste and Argonne groups. Our offline data analysis began even before the data run was over and by the end of 1990, the initial results were ready for publication. Final analysis of the charged pion and lambda production data was performed at Rice using our IBM RISC/6000 computer workstations. This analysis entailed complete reconstruction of approximately 25 million raw events.

We have final results for the analyzing power A for the inclusive production of π^+ , π^- and π^0 particles at high x_F , using 200 GeV/c polarized proton and antiproton beams. In addition, we have final results for the polarization (P), analyzing power, and spin transfer for inclusively produced Λ particles at high x_F . In the following section we present some of the highlights from the rather large amount of data which we have analyzed. These results contribute to our currently limited knowledge of high energy spin phenomena, and will provide insight into certain theoretical models and perhaps even to the spin structure of the proton itself.

The charged pion analyzing power measured with polarized protons is shown in Fig. 2a. A striking x_F dependence is apparent in which the magnitude of A increases with x_F for both π^+ and π^- data, but the signs are opposite, with A being negative for the π^- .

Fig. 2. The analyzing power for π^+ and π^- production by 200 GeV/c polarized protons:
 (a) integrated over all p_T , and
 (b) for pions above and below a p_T threshold of 0.7 GeV/c.

Fig. 3. The analyzing power for π^+ and π^- production by 200 GeV/c polarized antiprotons integrated over all p_T .

Note that A is very large at high x_F , up to 0.29 ± 0.09 for π^+ and down to -0.37 ± 0.07 for π^- . In addition, a dramatic threshold effect appears when p_T rises above 0.7 GeV/c. Fig. 2b shows A versus x_F for values of p_T above and below the threshold. It seems that the increase in the magnitude of A is an x_F -dependent effect above a p_T threshold. A plot of the charged pion analyzing power from the polarized antiproton beam is shown in Fig. 3. In this case, the signs are both reversed, and the magnitude of A for the π^+ data is roughly twice that for the π^- .

For π^0 production, A was measured in two kinematic regions: large x_F at small p_T (using the forward spectrometer), and large p_T at $x_F = 0$

(using the CEMC lead glass walls). Fig. 4a shows our results for A at high x_F measured with polarized protons. A rises with increasing x_F and reaches a value $A = 0.15 \pm 0.03$. This is consistent with our 1987 result¹.

Fig. 4. The analyzing power for π^0 production from 200 GeV/c protons and antiprotons for the following kinematic regions: (a) high x_F , and (b) high p_T and low x_F .

The antiproton data for the same kinematic range shows similar behavior in magnitude. In the high p_T region at $x_F = 0$, A is zero up to $p_T = 3.1$ GeV/c then decreases rapidly and reaches a minimum $A = -0.17 \pm .06$ at $p_T = 3.4$ GeV/c. In the range of p_T from 3.5 to 4.6 GeV/c the data indicates a change in behavior, however, the statistics are poor. Fig. 4b summarizes the above result. A short run with antiprotons yielded small values of A in the $p_T < 3.0$ GeV/c region with a hint of negative value at higher p_T . Another important parameter is the longitudinal parameter A_{LL} . It is found at 95% confidence level that $-0.1 < A_{LL} < 0.1$ for the polarized proton data and $-0.2 < A_{LL} < 0.1$ for the antiproton data.

For the high x_F inclusive Λ production, a clean sample of selected events gives the analyzing power A and depolarization D_{NN} in the x_F and p_T ranges $0.2 < x_F < 0.9$, $0.2 < p_T < 1.2$ GeV/c. Plots of A and D_{NN} are given in Fig. 5. The D_{NN} results are consistent with zero and agree with the only previous measurement, which we made at Brookhaven in 1988¹. The Λ polarization is observed to be increasing with both x_F and p_T , in a pattern similar to what has been previously observed by other experiments.

The general features of the data are consistent with a common explanation of spin phenomena using static SU(6) wave functions². In this model quarks produced are transversely polarized and the high x_F quarks in the proton remember the proton's spin. The value of A increases with x_F because a greater fraction of mesons are produced by fragmentation at high x_F and a single quark carries the spin of the proton a larger fraction of the time at higher Bjorken x . The reflected sign of A for oppositely charged pions is consistent with the up quark spin being aligned with that of the proton whereas that of the down quark is oppositely aligned. However, the magnitude of the analyzing power does not always agree with this model. Although perturbative QCD calculations do not apply in this kinematic region, the data presented here may be relevant to the "spin crisis"³. For the Bjorken sum rule to be satisfied, g_1 of the neutron must be more negative than expected in

conventional models⁴. That A for π^- production is more negative than expected may be a manifestation of a similar effect.

Fig. 5. The analyzing power and D_{NN} as a function of x_F for Λ Production from 200 GeV/c polarized protons.

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B. The SMC Experiment (CERN NA47)

Rice has assumed the lead role in a collaboration with Saclay and Trieste for the construction of a polarimeter to measure the muon beam polarization for the SMC experiment. This experiment will make the first measurement of the spin dependent structure function g_1^n of the neutron and will increase the accuracy of the SLAC-YALE and the EMC¹ measurements of g_1^p of the proton.

The spin-dependent structure functions of the proton and neutron contain the basic information about the spin composition of the nucleons and make possible important tests of QCD and of our models of the nucleon. These spin-dependent structure functions are independent of the exhaustively studied spin-independent structure functions. They are determined from measurements of spin-dependent asymmetries in the deep inelastic scattering of polarized electrons or muons on polarized nucleons¹.

The quantity which is measured in these experiments is

$$A_1(x) \equiv \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}},$$

where $\sigma_{1/2}(\sigma_{3/2})$ is the absorption cross section for polarized virtual photons by polarized nucleons when the total component of angular momentum along the collision axis is $1/2$ ($3/2$). The existing data are shown in Fig. 1.

A fundamental sum rule, originally derived by Bjorken² from current algebra but now recognised to be based on QCD in the scaling limit relates the first moments of the spin-dependent structure functions of the nucleon to the weak interaction coupling constants for neutron beta decay. It reads

$$\int_0^1 dx \left(g_1^p(x) - g_1^n(x) \right) = \frac{1}{6} \left| \frac{g_A}{g_V} \right| \left(1 - \frac{\alpha_s(Q^2)}{\pi} \right) = 0.191 \pm 0.002 \quad \mathbf{BJ}$$

$$\text{where } g_1^{p(n)}(x) = \frac{1}{2x} \frac{A_1^{p(n)}(x) F_2^{p(n)}(x)}{1 + R^{p(n)}(x)}$$

in which $F_2(x)$ and $R(x)$ have their usual meanings¹. The factor involving the strong coupling constant $\alpha_s = 0.27$ at $Q^2 = 10 \text{ GeV}^2$ is the correction to the zeroth order Bjorken sum rule due to perturbative QCD. In the naive quark-parton model

Fig. 1. Existing data on the quantity $A_1(x)$.

$$g_1^{p(n)}(x) = \frac{1}{2} \sum_i e_i^2 \left[q_i^{\uparrow}(x) - q_i^{\downarrow}(x) \right]$$

where i indicates the quark type with charge e_i and where $q_i^{\uparrow(\downarrow)}(x)$ is the probability that quark of type i with fractional momentum x of the nucleon has its spin parallel (antiparallel) to the nucleon spin. Hence $\frac{1}{2} \Delta q_i(x) = \frac{1}{2} \left[q_i^{\uparrow}(x) - q_i^{\downarrow}(x) \right]$ is the contribution of quark type i with momentum fraction x to the proton spin.

Auxiliary sum rules for the proton and neutron separately, which involve model-dependent assumptions (principally the validity of flavor SU(3) and that the strange quark sea is unpolarized) have been given by Ellis and Jaffe³

$$\Gamma_p = \int_0^1 dx g_1^p(x) = 0.189 \pm .005$$

EJ

$$\Gamma_n = \int_0^1 dx g_1^n(x) = -0.002 \pm 0.005$$

where the above numbers contain QCD corrections.

Thus far, experimental data are available only for the proton so that the Bjorken sum rule cannot be tested. However, EJ for the proton can be tested. From the CERN data alone it was found that¹

$$\int_0^1 dx g_1^p(x) = 0.114 \pm 0.012 \text{ (stat.)} \pm 0.026 \text{ (syst.)}$$

in substantial disagreement with EJ. Combination of the CERN and SLAC data gave¹

$$\int_0^1 dx g_1^p(x) = 0.116 \pm 0.009 \pm 0.019$$

Fig. 2 shows the CERN and SLAC data on the first moment of g_1^p as a function of the lower limit x of the integral, from which the above result is derived. Note that the low x region ($x < 0.1$), measured for the first time by the EMC group, was decisive in showing the violation of the Ellis-Jaffe sum rule. Assuming the Bjorken sum rule and the above experimental result, we conclude that Γ_n for the neutron is much more negative ($-0.075 \pm 0.009 \text{ (stat.)} \pm 0.019 \text{ (syst.)}$) than the value predicted by the Ellis-Jaffe sum rule.

Finally using the Bjorken polarization sum rule, the experimental results, and the naive quark-parton model relation, it follows that the fraction of the proton spin carried by quarks is $(3 \pm 9 \pm 17)\%$, giving rise to the so-called "spin crisis" in QCD. This unexpectedly small value implies that the spin of the proton is carried by gluons and/or orbital angular momentum.

From this introduction, it is clear that the measurement of the spin dependent structure functions of the proton and the neutron is a crucial next step. Briefly, such a measurement will accomplish the following goals.

- It will allow a test of the fundamental Bjorken polarization sum rule. This sum rule is obtained from QCD without model-dependent assumptions; hence its experimental verification will be of fundamental importance.
- It will provide a further basis for testing model-dependent sum rules, such as those from Ellis and Jaffe for the proton and neutron.

Fig. 2. The first moment of g_1^p as a function of the lower limit, x , of the integral.

- It will provide important new information and constraints concerning the spin-isospin structure of the nucleon.
- Such information is essential for understanding high energy scattering processes which involve polarized nucleons. These include hadron-hadron scattering, the polarized Drell-Yan process and production of polarized W or Z vector bosons in collisions of polarized protons in a high energy storage ring.

The asymmetry (A) for longitudinally polarized muons scattered by longitudinally polarized nucleons is defined as

$$A = \frac{d\sigma^{\uparrow\downarrow} - d\sigma^{\uparrow\uparrow}}{d\sigma^{\uparrow\downarrow} + d\sigma^{\uparrow\uparrow}}$$

where $d\sigma^{\uparrow\uparrow(\downarrow\uparrow)}$ is the cross section for parallel (antiparallel) muon and nucleon spins. It is derived from the measured asymmetry

$$A = \frac{A_{\text{meas}}}{P_\mu P_T f}$$

where P_μ and P_T are the beam muon and target polarizations and f is the dilution factor arising from unpolarized material in the polarized target. In first order QED, the asymmetry A is related to the virtual photon - nucleon asymmetries A_1 and A_2 by

$$A = D (A_1 + \eta A_2)$$

where D and η are kinematical functions. To a good approximation $A_1 = A/D$.

This experiment will measure the proton and neutron asymmetries A_1^p and A_1^n , thus determining the spin dependent structure functions in order to test the Bjorken sum rule with about 10% accuracy. The neutron asymmetry will be derived from the proton and deuteron asymmetries A_1^p and A_1^d by the relation

$$A_1^n = \frac{1 + \left(\frac{F_2^p}{F_2^n} \right)}{1 - 1.5 W_D} A_1^d - \left(\frac{F_2^p}{F_2^n} \right)$$

where W_D represents the D-state probability of the deuteron ($\sim 5\%$). The Bjorken sum rule will then be evaluated.

The experiment uses the EMC spectrometer (Fig. 3) with a new polarized target and a muon polarimeter added. The new polarized target system will provide polarized deuterons as well as polarized protons and will have the capability of rapid spin reversal with over 40% deuteron polarization.

To reduce the systematic errors on the measured asymmetries it is essential to reverse the nucleon spins frequently and thus rapidly. In this way effects due to drift in the acceptance are largely avoided.

The magnet construction will be completed at Saclay early next year. Construction of the cryostat will soon begin. In this run the old EMC target filled with a deuterated sample is being used, currently giving about 25% deuteron polarization.

The polarimeter was designed at Rice and is shown schematically in Fig. 4. Rice has assumed responsibility for the construction of the multiwire proportional chambers (MWPCs) downstream of the bending magnet (MNP26) and for the lead glass wall. Trieste has furnished the fast 1 mm beam chambers and Saclay the data acquisition electronics, two Sun work stations for data acquisition, on-line data analysis, and the trigger scintillation hodoscopes.

SMC EXPERIMENTAL SET-UP

Fig. 3. Plan view of the overall experiment.

Fig. 4. Schematic plan of the polarimeter for the muon beam.

Fig. 5. Dependence of the energy spectrum of the decay positrons on the muon polarization.

The muon beam polarization will be measured by two methods: (1) the shape of the energy spectrum of decay positrons in the laboratory system is sensitive to the muon polarization as is shown in Fig. 5; and (2) the muon spin will be analyzed by detecting the elastic scattering of muons from electrons in a polarized iron target.

In the decay method, the muons decay in a magnetic field free region of 30m, upstream of the MNP26 bending magnet. The shower veto counter (SV) insures that the incident particle was a muon, not a positron previously produced by muon bremsstrahlung or decay. The quadrupoles Q³⁴ and Q³⁵ refocus the muon beam which has blown up downstream of the polarized deuteron target. Decay positrons are deflected out of the incident beam into the downstream MWPCs and lead glass wall (LG) by the MNP26.

Fig. 6a. The difference between the tracked position of the downstream particle and the detected position of the cluster in the lead glass array. The offset is due to temporary misalignment.

The muon decay trigger is a pulse height greater than 10 GeV in the lead glass in coincidence with a single minimum ionizing particle in the shower veto counter (SV). Lead placed upstream of the SV initiates a shower for unwanted incident positrons, which are vetoed as multiple pulse heights by these crossed scintillation hodoscopes. Various veto counters (BV) suppress events initiated by beam halo particles. The positron momentum is then measured by the MWPC's, and compared with the clustered energy of the shower in the lead glass wall. The extrapolated track minus the lead glass cluster position has about a 2 cm width for 10 cm lead glass blocks as is shown in Fig. 6a.

Fig. 6b. Pulse height measured in the LG wall plotted as a function of particle momentum.

In Fig. 6b, the dark 45 degree stripe is due to the positrons of interest from beam muon decays upstream of the MNP26; in addition there is scattered background due to muon decays in the MNP26 and beam halo muon induced showers in the lead glass. The downstream hodoscope VLG, separated from the LG by a lead wall, detects halo muons which have initiated a shower in the LG. Cuts on the ADCs and TDCs of the SV, BV, LG and VLG, along with the requirement of energy and momentum matching on the positron track should eliminate backgrounds due to beam halo muons, decays not occurring in the decay region, and positrons produced upstream of the decay region.

The decay polarimeter is now fully operational and we expect to make a measurement of the muon beam polarization during the present data taking run. This will be the first high quality measurement of this type ever made, and should be of sufficient accuracy so that the beam polarization does not contribute to the error on the spin-dependent neutron structure function measured during this current data run.

The MWPCs, PPC4 and PPC3, were built by Rice graduate students and constitute an M.A. thesis project for Steve Eichblatt. The Rice students Eichblatt, Gaussiran, and Cranshaw, along with postdoctoral fellow Mark Lowe, have largely debugged the system and gotten it working. Mark Lowe has written, from scratch, an event reconstruction program which has allowed us to debug the polarimeter and is coordinator for the data analysis of the polarimeter. Lowe and the three Rice graduate students have been in residence at CERN without interruption for the entire run and have contributed a major fraction of the work in the setup and debugging of the polarimeter.

For 1992 and following runs, we will also implement the μ -e scattering polarimeter (Fig. 7). This requires the construction of one additional MWPC (PPC1), a special large 1mm wire spacing chamber. We will construct this in collaboration with the Saclay shops,

Fig. 7. Schematic of the muon - electron elastic scattering polarimeter.

using a design developed at Rice. This chamber must count efficiently in the region of the muon beam, as the Trieste built beam chambers do, but must also cover the complete solid angle for μ -e scattering. The design is now final. The chamber will be constructed either at Saclay or at Rice, and the PCOS III electronics will be furnished by Rice. We also must furnish faster photomultipliers than are current on the LG wall. The photomultipliers were donated to us by BNL along with the lead glass, but to fully implement the polarimeter we must purchase the faster photo tubes. This is of modest cost (\$30K) compared to that of the total polarimeter and still represents a considerable savings over the originally projected cost of the lead glass wall. We are also utilizing three MWPCs built for FNAL experiments E704 and E683 to reduce the total cost.

Trieste will furnish four more beam chambers and Saclay (in addition to the 1mm MWPC) the polarized Fe target. The Fe target will have the capability of polarization reversal on alternate SPS pulses to reduce systematic errors. We expect using the two polarimeter techniques to reduce the error on the beam polarization measurement so that it never contributes to the final error on g_1^n of the neutron or to the check of the Bjorken sum rule.

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C. FNAL E683 – Photoproduction of Jets

In Fermilab experiment E683 we are studying the photoproduction of jets in the Wide Band photon beam. Rice is the lead institution on this experiment and M.D. Corcoran is the spokesperson. Collaborating institutions are Ball State University, Fermilab, University of Iowa, University of Maryland, University of Michigan, Vanderbilt University and University of Wisconsin. The Wide Band Beam at Fermilab provides the world's highest energy tagged photon beam, with usable photon fluxes extending to 400 GeV. The large-solid-angle coverage of our calorimeters, including full coverage in the forward direction, provides us with a unique opportunity to study the direct-coupling of the photon to partons in the target nucleons. The first-order QCD processes of interest are the QCD Compton and photon-gluon fusion diagrams. In some cases, the photon first dissociates into a quark-antiquark pair before it interacts. Events of this type, instead of just being a nuisance, will allow us to obtain new information on the photon structure function. Complete second-order calculations have been done by Jeff Owens of Florida State, who has helped us a great deal in understanding and applying his work.

In addition to studying jet photoproduction with a hydrogen target, the A-dependence of jet photoproduction is of considerable interest. We know from our previous experiment E609 that large A-dependent effects are seen in jet production in p-A interactions. Some new results on A-dependent effects have recently been published from E609 (Ref 1). The data are consistent with a significant amount of multiple-scattering of the partons as they exit the nucleus, with hadronization occurring outside the nucleus. Whether or not the same effect occurs in photon-induced jet production is an interesting and unanswered question. Therefore in addition to taking data with a hydrogen target, we will take data with six nuclear targets ranging from Be to Pb, and we will have two or three deuterium fills of the cryogenic target.

After a short test run in August of 1990, E683 was ready for data. We took advantage of a scheduled three-month shutdown to make some necessary repairs and to add a detector upstream of the lead radiator to monitor beam pile-up. The three-month shutdown grew to 4.5 months, and we were ready for startup in January. However, in mid-December, shielding problems were discovered in several of the external beam lines and in the accelerator itself, and startup was delayed until late June. The first useful beam for data was in early July. For the first month the accelerator ran at low intensity and was plagued with normal start-up problems. Nevertheless, there have been periods of stable beam in the last month, and we have eagerly put them to use.

Beam Tagging

A crucial part of the beamline is the tagging of the electron beam using the Si microstrip detectors provided by the Milano group from E687. With a momentum spread of $\pm 15\%$ in the electron beam, it is necessary to measure the momentum of each electron, which is accomplished to an accuracy of 2% with the Si tagging system. For calibration, when the beam was collimated so that the Si tagging detectors have full coverage, the tagging efficiency often exceeded 90%. For regular data-taking, with collimators completely open, the efficiency at low intensities approached the maximum possible 85% due to the acceptance of the microstrips. At higher intensities the efficiency drops somewhat due to multiple occupancy of buckets, but even at our normal running intensity we achieve tagging efficiencies of about 65-70%. Fig. 1 shows the energy spectrum of the incident electron beam as measured by the Si microstrip detectors. After the lead radiator, a

Fig. 1. The energy spectrum of the Wide Band electron beam as measured by the silicon microstrip detectors.

series of shower counters measures the energy of the recoil electron, allowing us to deduce the energy of the bremsstrahlung photon to an accuracy of 2-3%.

Calorimeter Calibration

A plan view of the experimental apparatus is shown in figure 2a. The most important part of our apparatus is a highly-segmented, sampling calorimeter. The

Fig. 2. a) Plan view of the apparatus. b) Segmentation of the sampling calorimeter.

segmentation of this detector is shown in figure 2b. Each tower consists of one layer of lead-scintillator sandwich, followed by three layers of iron-scintillator sandwich. Both the EM and hadronic energy resolutions are important in the data analysis and must be measured with care. This necessitates a careful calibration of the entire detector. We calibrated each of the 132 towers with 90 GeV electrons, and twelve towers were calibrated with electrons of 30 GeV, 60 GeV, and 150 GeV as well. Twelve regions of the calorimeter were calibrated with pions of energies 30, 60, 100, and 150 GeV. From a preliminary analysis of the calibration data, we show typical results in Figs. 3a and 3b. The energy resolution for both EM and hadronic particles is well within expected values. The constant factors quoted include the resolution of the beam tagging, so they will be somewhat smaller when that contribution is removed.

Fig. 3. Energy resolution measured in the main calorimeter for:
 a) Electromagnetic showers, and b) Hadronic particles.

One of the distinctive aspects of photoproduction is the expected absence of forward energy for high p_t events. The beam calorimeter, which measures forward energy flow, is therefore crucial and must be calibrated with care. This was completed early in the

Fig 4. Measured energy resolution for the beam calorimeter for:
 a) EM, and b) hadronic particles.

run, and preliminary results for both the EM and hadronic response are shown in Figs. 4a and 4b. Due to the coarser sampling in the beam calorimeter, the energy resolution is not quite as good as for the main calorimeter, but still well within acceptable values.

Preliminary Results

The calibration data were interspersed with preliminary photon data, so that all trigger logic and timing could be checked. All trigger hardware was found to be functioning, and we began data-taking within two weeks of accelerator turn-on. As of this writing (August 14, 1991) we have completed all preliminary checkouts and calibrations of our apparatus and have entered into production data-taking. So far we have about 1.5 million triggers from hydrogen and 0.7 million triggers from the solid targets.

Fig 5. A typical spectrum of photon energy measured in the main calorimeter for events which pass a high- E_t trigger.

Figure 5 shows a typical spectrum of photon energy for events which pass one of our high- E_t triggers. Even a modest E_t requirement in the main calorimeter is sufficient to discriminate against all EM background. The minimum photon energy we are sensitive to is about 100 GeV.

Figure 6a shows the ratio of energy observed in the main calorimeter to the energy of the incident photon. Figure 6b shows the ratio of the total energy observed in both calorimeters to the photon energy. Although the absolute energy scale of our calorimeters has not yet been determined to better than 10%, it is clear that we see nearly all of the incident energy. The high-energy tail is due to pileup in the beam calorimeter from electrons in nearby RF buckets. Information from our pileup monitor, located upstream near the Si tagging stations, will allow us to eliminate or make corrections for events with pileup.

Fig. 6. a) The ratio of energy measured in the main calorimeter to that of the incident photon. b) The ratio of the total energy measured in both calorimeters to the energy of the beam photon.

Figure 7 shows a typical E_t distribution in the main calorimeter for events satisfying a "global" trigger, which is a threshold requirement on the total E_t in the calorimeter. Above threshold the distribution is seen to be exponential. Figure 8 shows two "lego" plots of jet-like events.

Fig. 7. A typical E_t distribution in the main calorimeter for events satisfying a "global" trigger.

Fig. 8. "Lego" plots of two jet-like events.

One potential problem in the analysis is the presence of soft photons accompanying the high-energy photon which interacted. The soft photons will typically enter the beam calorimeter; the problem is to discriminate them from energy in the beam calorimeter from the hadronic interaction of the energetic photon. To study this problem, we have taken some fraction of the data with a thinner lead radiator (10% vs 20%) and we have taken some data with a pion beam. We see a clear difference in the EM fraction of energy in the beam calorimeter for a pion beam compared to a photon beam. The difference can be attributed to soft photons, and we are currently studying ways to correct for the effect.

We are expecting to continue data-taking through the end of November or December 1991. We are pleased with the quick startup of the experiment and the quality of the data taken so far. There are six Ph.D. students on E683 (three from Rice and three from other institutions), and two Masters students from Rice. Data analysis tasks will be divided up among the various institutions.

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D. The SDC Detector Design and the FNAL D0 Experiment

During the last year, Bonner Lab was involved in the design of the D0 upgrade at FNAL¹ and the SDC experiment for the SSC². Our work in D0 centered around the design of a new magnetic tracking system intended to replace the existing non-magnetic one. In the SDC, we contributed to the central tracking, physics and detector performance, computing and simulation and muon subgroups.

There is considerable overlap between the D0 upgrade and SDC tracking system designs. Both include a magnetic solenoid with silicon strips near the interaction region surrounded by an outer tracker. We are a member of the fiber tracking group (FTG) which has developed scintillating fiber designs for these outer tracking systems. Although there are competing designs, we believe that the fine-grained nature of scifi detectors will allow us to deal with complex events and event overlaps in an affordable manner. The primary contribution of the Bonner Lab group has been the development of software to simulate the response of such a detector and for pattern recognition and track reconstruction.

The scifi simulation program SFTSIM was largely completed in 1990 although some refinements have been added during the last year. In collaboration with UTD (University of Texas at Dallas) we ported the program to the SDC simulation framework SDCSIM to make it easily available to other members of the SDC and so that it could be used in combination with other parts of the detector. We have also completed much of the effort required to move into the D0 framework. In both cases, it is essential to study the combined pattern recognition and reconstruction capability of the entire tracking system since cost and material constraints will not allow the luxury of redundant systems. The program and some early occupancy results were described at the Fort Worth SSC meeting last fall³.

An important contribution of the Bonner Lab during the last year has been the development of the track reconstruction package TRF. This program clusters the hit fibers, combines stereo and axial measurements to obtain space points and then links the points to identify and reconstruct tracks. Although this road-following technique is CPU-intensive, it is very efficient and well suited to assessing the pattern recognition potential in various designs of a tracking system. Although this program is still under development we have used it to carry out two studies this summer.

Last June, we simulated a D0 detector with four scifi superlayers and three silicon barrels as described to the PAC review in May 1991⁴. We also included the silicon disks for material but did not use them in the reconstruction. Performing 2D (r - ϕ) reconstruction, we were able to identify more than 90% of the candidate tracks in $t\bar{t}$ events where W 's decay to muons. Candidate tracks are those that came from the vertex and reach the outer scifi superlayer without significant interaction. We reconstructed only one false track per event with $p_T > 1\text{ GeV}/c$. We are currently working on extending this study to include full 3D reconstruction.

In July we reconstructed events using only the scifi part of the proposed SDC tracking system piling up one to six QCD (minimum bias) events⁵. We performed 3D reconstruction and were able to find 98% of the candidate tracks. When we included six events in a crossing, the ratio of false to true tracks was 0.2 pointing out the need for the interior silicon layers. We plan to extend these studies to include the silicon and to reconstruct more interesting events.

Our contributions to the "physics" of the SDC detector included a study of the detection of a second Z boson^{6,7}. We demonstrated that the SDC detector would be able to distinguish particular couplings by providing a measurement of forward-back asymmetry in leptonic decays of the Z'. We found that there would be little advantage in extending the coverage of the detector past eta of 2.5 but the measurement would be seriously diluted if the coverage only extended to eta of 1.5.

We also compared minimum bias measurements from UA1, UA5 and CDF with predictions from the event generator Pythia, tuning parameters to fit the data⁸. The results are used to predict behavior at the SSC energy and are provided to the collaboration through the simulation package SDCSIM.

We contributed to the computing and simulation subgroup by providing the GEANT interface SG to the collaboration-wide detector simulation and event reconstruction package SDCSIM. We also aided in the global design and implementation of the package. SDCSIM is important both to provide the information we need for our present detector design studies and as a model of our final system for software development and distribution.

We have participated in the design of the SDC muon system through our involvement in E821, an experiment in the NWA test beam at Fermilab. This experiment will measure the flux and energy spectrum of soft neutrons produced from hadron showers in a calorimeter. Knowledge of this flux is needed to resolve questions about the muon trigger. E821 is expected to have two weeks of dedicated beam time in October or November of 1991.

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- ² Letter of Intent by the Solenoidal Detector Collaboration, SSCL (Nov 1990)
- ³ David Adams *et al.*, Symposium on Detector Research and Development for the SSC, World Scientific (1991)
- ⁴ David Adams, D0 note 1177, FNAL, June 1991
- ⁵ David Adams, Proceedings of the August 1991 SDC meeting at LBL
- ⁶ G. Eppley and H. Miettinen, SDC note SDC-90-00125, (Nov 1990)
- ⁷ G. Eppley and H. Miettinen, SDC note SDC-91-00009, (Mar 1991)
- ⁸ G. Eppley, SDC note in preparation

E. Instrumentation Projects

1. Lead Glass Array for CERN NA47

The lead glass wall which we used for BNL E817 was dismantled and reconfigured to build a lead glass calorimeter for the SMC polarimeter. Our design called for an area of 30 cm x 100 cm of SF5 lead glass. Since we possessed 60 blocks with a length of 21.4 cm, and a square face of edge 10.14 cm, we decided to improvise. The length of each block is 14.7 radiation lengths, which is insufficient for the present application; therefore we glued pairs of blocks together to make the total thickness a more than adequate 29.4 radiation lengths. The counters were stacked in three rows with 10 blocks per row. Thirty PMT's (RCA 4900) were attached to the back of the lead glass blocks. A light tight container and transporter for this lead glass wall was designed and constructed at Rice.

The entire system was assembled and tested at Rice before being sent to CERN in March. During beam tests in June, we found that the transit time of the RCA tubes is simply too slow to allow building a fast first level trigger for the very inflexible RMH electronics used for the Trieste beam wire chambers. We must therefore replace the slow RCA tubes by a faster tube, possibly the Hamamatsu R2238, and this will allow the complete lead glass system to be used for the 1992 data taking period.

2. MWPC Detectors and Electronics for CERN NA47

Two large planar MWPCs (PPC3 and PPC4) were constructed by Rice graduate students and instrumented at Rice for the SMC experiment at CERN. These chambers are now being used as tracking chambers in the SMC polarimeter. The Rice students S. Eichblatt, T. Gaussiran and J. Cranshaw along with post doctoral fellow M. Lowe have largely debugged the PCOS III electronics and read out system. An event reconstruction program for the polarimeter has been written by the Rice group and we are taking a major role in the polarimeter data analysis.

For 1992 and subsequent runs, we will implement the μ -e elastic scattering polarimeter which requires the construction of one additional MWPC (PPC1), a large 1 mm spacing wire chamber. The design of this special chamber has been developed at Rice and the construction of this chamber will be done at the Saclay shop and/or at Rice in collaboration with the Saclay group. This chamber must count efficiently in the muon beam, as do the Trieste-built beam chambers, but in contrast it covers the complete solid angle for muon electron scattering – about a factor of four larger than the beam chambers. The front end and the readout electronics (PCOS III) from LeCroy will be furnished by Rice for this chamber.

G. 1991 Publications, Presentations, and Theses

- "Analyzing Power in Inclusive π^+ and π^- Production at High x_F with a 200 GeV Polarized Proton Beam", D.L. Adams *et al.*, FNAL E704 collaboration, accepted for publication by Phys. Lett. B, June 1991
- "Comparison of Spin Asymmetries and Cross-Section in π^0 Production by 200 GeV Polarized Protons and Antiprotons", D.L. Adams *et al.*, FNAL E704 collaboration, Phys. Lett. B261, (1991) 201-206.
- "First Results for the Two-Spin Parameter A_{LL} in Inclusive π^0 Production by 200 GeV Polarized Protons and Antiprotons", D.L. Adams *et al.*, FNAL E704 collaboration, Phys. Lett. B261, (1991) 197-200.
- "Large- x_F Spin Asymmetry in π^0 Production by 200 GeV Polarized Protons", D.L. Adams *et al.*, FNAL E704 collaboration, Fermilab preprint Pub-91/13-E.
- "High- x_T Single-Spin Asymmetry in π^0 and η Production at x_F by 200 GeV Polarized Anti-Protons and Protons", D.L. Adams *et al.*, FNAL E704 collaboration, Fermilab preprint Pub-91/14-E, submitted to Physics Letters.
- "Evidence for Multiple Scattering of High Energy Partons in Nuclei", M. D. Corcoran, *et al.*, FNAL E609 Collaboration, Physics Letters B259 (1991) 209.

Publications in preparation

- "Analyzing Power in Inclusive π^+ and π^- Production at High x_F with 200 GeV Polarized Anti-Protons", D.L. Adams *et al.*, FNAL E704 collaboration, in preparation, to be submitted to Phys. Rev. Lett.
- "Spin Parameter Measurements in Inclusive π^+ , π^- , and Λ Production at High x_F with 200 GeV Polarized Protons and Anti-Protons", D.L. Adams *et al.*, FNAL E704 collaboration, in preparation, to be submitted to Phys. Rev. D.

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- "Analyzing power in inclusive π^+ , π^- , and Λ production at high x_F with 200 GeV polarized protons", J.D. Skeens for the FNAL E704 collaboration, Proceedings of the 4th Conference on the Intersections Between Particle and Nuclear Physics, Tucson, AZ, May, 1991.
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- Jack M. Cranshaw, "The Lambda Trigger for the E704 Forward Spectrometer", M.A., Rice University, January 1991.
- Joseph L. White, "Measurement of the Analyzing Power in Inclusive, High x_F Charged Pion Production with a 200 GeV/c Polarized Proton Beam", Ph.D., Rice University, May 1991.
- Chau Nguyen, "Spin Effects in Inclusive Λ Production Using 200 GeV Polarized Protons", Ph.D., Rice University, June 1991.

3. TASK B – Theoretical High Energy Physics

A. Progress on Theoretical Topics

During the past year we have been fortunate to have extended visits from Dr. Uwe Ritschel, who visited for four months, and Dr. Lutz Polley, who visited for five weeks from the University of Oldenburg, Germany. These visits were funded by German government agencies. Both visits were very productive.

With Dr. Ritschel we recently completed a paper on the Gaussian effective potential (GEP) for $O(N)$ symmetric $\lambda\phi^4$ theory in an unconventional large- N limit. The GEP is known to yield the exact result in the conventional large- N limit, where λ is required to scale as $1/N$. However, the GEP's phase transition occurs only when $\lambda \gg 1/N$ (in units of the physical mass in the symmetric vacuum). This means that the phase transition lies outside the reach of the $1/N$ expansion. Our analysis shows that the critical λ at the GEP's phase transition is:

$1/4$	in 0+1 dimensions;
$(\pi/2)/\ln N$	in 1+1 dimensions;
$(\pi/2)g^{5/3}/N^{1/3}$	in 2+1 dimensions (with $g=(\sqrt{5}+1)/2$);
$\pi^2 \epsilon/\sqrt{N}$	in $(3-\epsilon)+1$ dimensions,

where the last case corresponds precisely to the positive, infinitesimal bare coupling constant of “autonomous” $\lambda\phi^4$ theory. All the renormalizations needed to obtain the “autonomous” theory emerge naturally from the requirement that the theory is close to its phase transition. Our analysis makes clear why the “autonomous” theory is not seen in the $1/N$ expansion, and shows it emerging as a natural extrapolation from lower dimensions. Another interesting result is that, in 1+1 dimensions and below, the GEP's first-order phase transition becomes asymptotically second order as $N \rightarrow \infty$.

Much of our recent work has centred on two complementary approaches to improving upon the Gaussian effective potential (GEP). One approach is the post-Gaussian expansion, which is a systematic, generalized perturbation-theory approach which can be formulated in a covariant functional-integral formalism. Our two papers calculating explicitly the second-order corrections in the $\lambda\phi^4$ case have now been published. Recently, Ion Stancu has investigated the post-Gaussian corrections in the case of the Liouville Model (a 2-dimensional theory with an exponential potential term). The interest in this model, apart from its possible importance in String Theory, is that its exact effective potential is known¹, and the GEP gives exactly the same shape². However, error estimates for the GEP do not vanish^{2a}, so presumably the vacuum-energy constant differs from the Gaussian result. Stancu's explicit calculation shows that, indeed, the second-order corrections change the vacuum-energy constant, but do not modify the shape of the effective potential.

As a complementary approach we have been studying variational calculations with non-Gaussian trial wavefunctionals. While less systematic than the expansion method, this approach remains a variational approximation, and thus has an attractive physical interpretation and maintains the variational inequality. Thus, we can be sure that we are improving the approximation if we succeed in lowering the energy (for fixed bare parameters).

The idea of the method is to write the trial wavefunctional as a unitary operator acting on a general Gaussian wavefunctional. In order for the transformation to generate a non-Gaussian wavefunctional, it needs to be the exponential of an operator that is at least cubic in the field operators and their canonical conjugates. We have explored a variety of transformations in the simpler case of Quantum Mechanics (undergraduate Tim Polley made valuable contributions to this part of the work). For scalar fields there are three non-trivial possible cubic operators, and in our paper we have studied two of these in detail. The calculation involves two functions that act as “variational parameters”, and the optimization of these functions leads to integral equations. We were able to find a solution to these equations in the unbroken-symmetry vacuum. A detailed paper on this work was completed, and we are working to try to explicitly renormalize the resulting effective potential.

A way of re-formulating at least some of these non-Gaussian variational calculations in a covariant, functional-integral formalism emerged from discussions with our visitors, Drs. Ritschel and Polley. It is based on the Jensen inequality for expectation values of convex functions (in particular, the exponential function):

$$\langle e^{-S} \rangle \geq e^{-\langle S \rangle}$$

By making a change of variables in the functional integral one can obtain approximations to the effective potential which go beyond the Gaussian approximation but which are still upper bounds on the exact result. The formalism also allows one to calculate the full effective action in a more satisfactory way than has been done in the past. Applications of this approach are being studied further.

Finally, we have been making progress on applying the GEP to scalar electrodynamics, as the simplest model that shows the Higgs mechanism. Using our manifestly covariant post-Gaussian expansion formalism we have verified our earlier, unpublished, Hamiltonian-formalism results, giving us confidence in our handling of the gauge-fixing and ghost problems. The results show an “autonomous”-like $\lambda\phi^4$ sector, whose symmetry breaking gives mass to the vector boson. There is a “perturbative” region of parameter space where the results correspond to Coleman and Weinberg's³ 1-loop analysis, and where the Higgs is much lighter than the vector boson. However, in other regions of parameter space the situation can be very different. We plan to write up these results soon.

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