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MEDIUM ENERGY MEASUREMENTS OF N-N PARAMETERS

Progress Report

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MEDIUM ENERGY MEASUREMENTS OF N-N PARAMETERS

I. OVERVIEW

We report here progress made during the three year period January 1, 1990, to December 31, 1993, for the Department of Energy Three-Year Grant No. DE-FG05-88ER40446, third year. A major part of the work has been associated with nucleon-nucleon (N-N) research carried out at the Nucleon Physics Laboratory (NPL) at the Los Alamos Meson Physics Facility (LAMPF). During this period we also completed data acquisition and analyses of a TRIUMF experiment, but we have no further plans for experimental work at TRIUMF. Other research has been and will be continued to be carried out at BNL, and involves two rare kaon decay experiments, BNL E791, now completed, and a second generation rare kaon decay experiment, E871, which has just this summer completed an engineering test run. We are now also members of a proposed experiment, **STAR**, (Solenoidal Tracker at RHIC) to be carried out at the Relativistic Heavy Ion Collider facility, RHIC, at BNL.

The past three years have been a time of rapid change in the focus of our experimental program. A LAMPF experiment, E1097, in which we spent a large amount of effort during the past three years, was terminated due to funding shortages after we had fabricated the detector, but before data acquisition, and consequently we increased our participation in the rare kaon experiment at BNL, E871. It now appears that there will be no LAMPF N-N program after 1993, so that our research efforts will concentrate on the BNL rare kaon decay measurement, E871, and on **STAR**. We expect that **STAR**, which requires the fabrication of a large colliding beam detector facility, will use an increasing amount of our research efforts during the next few years.

In what follows we will describe recent progress on our LAMPF and TRIUMF N-N measurements, on our BNL rare kaon decay work, and on our initial work with the **STAR** group.

A. N-N Measurements at LAMPF and at TRIUMF

Broadly speaking, the aim of the N-N experimental program has been the determination of the nucleon-nucleon amplitudes at medium energies. The required data include both elastic and inelastic experiments, and in addition the measurement of polarization and polarization transfer parameters. Our recent LAMPF nucleon-nucleon experiments have consisted of the following:

(1) *Spin transfer measurements in np elastic scattering (E876)*. This experiment was carried out in two phases. Phase 1, completed during the summer of 1991, consisted of

the measurement of the four spin-transfer observables K_{LL} , K_{SS} , K_{SL} and K_{LS} at 485, 635, and 788 MeV. The data and their analyses are described in two Physical Review C publications[1,2]. In Phase 2 the observables A_{N0} , P , and K_{NN} were measured at the same three energies. Both Phase I and Phase II data are proving invaluable in fixing the isospin 0 phase shifts and amplitudes.

(2) *K_{LL} and P for np Elastic Scattering (E1234)*. Our measurements of the neutron beam polarization for E876 uncovered a significant disagreement with our previous measurements of $K_{LL}(d)$ at 800 MeV, suggesting that our previous LAMPF np elastic analyzing power data should be renormalized. Consequently, we wrote and submitted a new proposal, (E1234), " K_{LL} and P for np Elastic Scattering." Our subsequent new measurements of the spin-transfer parameter K_{LL} at 0° clarified the normalization discrepancy. These measurements, which are in good agreement with theoretical predictions, have also been published[3].

(3) *Forward angle (n,p) analyzing power measurements(E1293)*. The energy dependent fit to A_{N0} , deduced from our E876 data, diverges from the single-energy fits above 500 MeV. This may result from inadequate data at energies about 800 MeV, which influence the 800 MeV solutions by constraining the phases to follow smooth curves. Cross calibration would help to tie together the normalization of different data sets. By extending our analyzing-power measurements to forward angles, we can tie together the normalization of the forward- and backward-angle peaks and also tie the np to the pp normalization via quasifree measurements. Analyzing-power data are also a sensitive probe of the higher partial waves which are sensitive to isospin-0 inelasticity. Consequently, we wrote and submitted a second new proposal, "(np) Elastic Analyzing Power" (E1293). These measurements have been carried out during the summer of 1993, and will be analyzed during the late fall of 1993.

(4) *p-p elastic absolute cross section measurements (E1072)*, with the goal of measuring the p-p differential cross section at LAMPF energies to an absolute accuracy of 1%. The experimental measurements were carried out during the summer of 1988. Analysis required careful evaluation of detector efficiencies, backgrounds, and a thorough study of beam attenuation in the target and surrounding materials. These measurements have now also been published[4].

(5) *n-p inelastic polarization measurements (E1097)*. For some time now we have been working on a LAMPF experiment, "Single Pion Production in np Scattering(E1097)," designed to measure the cross section and analyzing powers for the reaction $np \rightarrow pp\pi^-$. We designed and fabricated a cylindrical drift chamber to surround the target, and spent a large amount of effort in the testing and development of this chamber. We carried out preliminary testing of our chamber and its associated electronics at LAMPF during the summer of 1991, and completed this work during 1992. The phase I run, using an unpolarized liquid hydrogen target, was expected be carried out during the summer of 1993, and the phase II run, using a polarized (frozen spin) target, in 1994.

E1097 was reviewed "in depth" by the LAMPF PAC on August 18, 1992, and received, as it had before, an A⁻ priority. The subcommittee report read, in part, *"The subcommittee is of the opinion that successful measurements of the differential cross section would contribute significantly to the understanding of the I = 0 NN interaction and of pion production processes..... All efforts should be directed to the cross-section measurements, but there is a risk that they will not be attained by the end of 1993.Recommendation: 500 hours of 800-MeV beam in BR with A⁻ priority."*

Subsequently, Peter Barnes, the Director of LAMPF, in reviewing the PAC recommendation, made the following comments *"I concur with the Subcommittee's recommendation of 500 hours of 800 MeV beam with A⁻ priority ... I also note that substantial MP-Division resources will be required to implement this experiment. I urge you to explore ways of augmenting the manpower on the experiment. I request a written update in early November, 1992, addressing the manpower questionAt that time I will decide if further MP-Division resources can be committed to your experiment."*

We met with Cyrus Hoffman, LAMPF Associate Director for Research, in early November, 1992. By then the Ron Ransome, Rutgers, and Charles Davis, University of Manitoba, had made strong commitments to E1097, so that we felt we most certainly had addressed the manpower question. We had carried out comprehensive GEANT simulations, which indicated that we could measure successfully the $np \rightarrow pp\pi^-$ differential cross section measurements, and finally, we had shown that we could successfully use multiplexing to reduce FERA and cable costs without seriously compromising the experiment measurements. However, Peter Barnes' decision, based by Cyrus Hoffman's report, was negative, and read in part: *"...E-1097 requires a significant investment of LAMPF funds, for electronics, cryogenics, and mechanical assembly, that simply are not available this year....As a result of this decision, no further LAMPF resources will be spent on E-1097. In fact, some of the FERA electronics previously bought for E-1097 may well be needed elsewhere in the LAMPF program...."*

Essentially, after three years development work, we now had a working detector but no experiment. Consequently, David Ambrose and Patrick Coffey, both of whom expected to carry out their Ph. D. dissertation research on this experiment, moved to BNL to carry out their Ph. D. dissertation research on the rare kaon decay experiment, E871.

(6) *Single pion production in np scattering at TRIUMF (E372).* During the past three years we have been involved in a neutron-proton inelastic scattering experiment at TRIUMF "Single Pion Production in np Scattering(E372)," designed, as was LAMPF experiment 1097, to measure the cross section and analyzing powers for the reaction $np \rightarrow pp\pi^-$. This experiment measures the same quantities as E1097, Phase I, proposed at the higher LAMPF energies. Our polarized neutron beam energy in E372 was 440

MeV. Our data taking runs for E372 were carried out during September, 1990, and February, 1991. The data were analyzed here at the University of Texas by Mark Bachman, whose Ph. D. dissertation was based on the data and its analyses.

The E372 spokesman was Norm Davison, of the University of Manitoba. Our initial plan was to carry out track and event reconstruction at the University of Manitoba, and final event analysis at the University of Texas. Track reconstruction proved especially difficult, and the initial software were inadequate. In addition, Norm left the field of medium energy physics soon after we had completed taking data, so that the analysis software was developed by Mark Bachman at the University of Texas, and the track and event reconstruction were carried out by Mark. Consequently, the analyses of the data were not completed until spring, 1993, more than two years after we had completed the data taking for the experiment. In spite of many difficulties, the data are very interesting, and demonstrate beyond all doubt the value and necessity of measuring spin observables in the study of this and similar reactions.

To summarize our N-N work, with the inclusion of our p-p absolute differential cross section data, Bugg and Bryan report stable solutions for the first time near 650 MeV for both isospin-0 and -1 and near 720 MeV for isospin-1 only. Near 800 MeV the phase-shift solutions agree for the first time with precise measurements of the pp total cross sections. The determination of the isospin-1 amplitudes can be considered complete from 500 to 800 MeV. Our spin transfer measurements in np elastic scattering (E876) have clarified the renormalization problem, which affects previous LAMPF data, and complete the set needed to extract the nucleon-nucleon scattering amplitudes near 500, 650, and 800 MeV. We expect that the forward angle (n,p) analyzing power measurements, completed during the summer of 1993, will provide the cross calibration needed to tie together the normalization of different data sets, and will resolve the problem of the divergence of the energy-dependent A_{N0} fits from the single-energy fits above 500 MeV. The major remaining weakness is with the inelasticities. Although the TRIUMF experiment has been successful, the higher energy np $\rightarrow$ pp π^- spin-dependent measurements proposed for LAMPF are badly needed to help resolve our very limited knowledge of $I = 0$ in elasticities.

B. A Search for Very Rare K_L^0 Decays: BNL 791/871

In the Minimal Standard Model (MSM) the decay $K_L^0 \rightarrow \mu e$ is forbidden by conservation of electron and muon additive quantum numbers. Its observation would be the first direct evidence of physics beyond the MSM. The decays $K_L^0 \rightarrow \mu\mu$ and $K_L^0 \rightarrow ee$ are permitted in the MSM, but are highly suppressed. $K_L^0 \rightarrow ee$ has not yet been seen, and observation of a branching ratio for this process that is significantly above MSM predictions would also be evidence for new physics.

BNL E791, a high sensitivity search for $K_L^0 \rightarrow \mu e$ and $K_L^0 \rightarrow ee$, completed data-taking at the Alternating Gradient Synchrotron facility (AGS) of the Brookhaven

National Laboratory in 1990, the year in which our group joined the experiment. The E791 spectrometer provided precise tracking with good (redundant) particle identification. Very high rate capability was achieved using custom built front-end electronics, a large parallel readout architecture, and a multi-level trigger system utilizing SLAC 3091/E emulators. The single event sensitivity to the decay $K_L^0 \rightarrow \mu e$ achieved by E791 is $< 3.3 \times 10^{-11}$ [5]. The E791 collaboration concluded that more running with the same apparatus is not an attractive way to make further gains. Therefore, a new collaboration— with substantial overlap with E791— was formed to perform a new search for $K_L^0 \rightarrow \mu e$ and similar modes. A new proposal was written, E871, "A New Search for Very Rare K_L Decays," (Spokesmen; W. R. Molzon, University of California, Irvine, S. G. Wojcicki, Stanford, and J. L. Ritchie, University of Texas), and was presented to the BNL Program Advisory Committee on November 8, 1990. The aim of the new experiment is to build on the experience of E791, the most sensitive kaon decay experiment performed to date, and to re-use some of the E791 equipment. Through increased acceptance, higher rate-handling capability, and improvements in several detector systems, the experiment should reach a single event sensitivity below 2×10^{-12} . At this sensitivity, a few decays of the type $K_L^0 \rightarrow ee$ should be observed if the decay occurs at the Standard Model level, along with about 10,000 $K_L^0 \rightarrow \mu\mu$ decays. The experiment is possible because of the increased beam flux made available by the AGS Booster.

The two physics graduate students who previously had been working on LAMPF E1097, David Ambrose and Patrick Coffey, are now participating in E871, and expect to complete their dissertation research on this experiment. A successful engineering run was completed in July, 1993, with data runs to follow in 1994 and 1995. Fabrication and testing of detector components are continuing.

C. STAR (Solenoidal Tracker at RHIC)

Recently, we have joined a large collaborative group working on the RHIC experiment STAR (Solenoidal Tracker at RHIC) at BNL. For the next several years this project will emphasize the design and fabrication of a very large, complex collider detector. The STAR detector is presently conceived of as a combination of a silicon vertex tracker (SVT), a Time Projection chamber (TPC), a set of trigger scintillators, and time of flight (TOF) counters. There is also an external TPC (XTPC) and some MWPCs. In addition, an electromagnetic calorimeter has been proposed, which would not only allow the detection of gammas, but would allow for some important measurements of spin dependence at high P_T (> 10 GeV/c) with polarized colliding protons that relate to the gluon spin structure functions. Funds for engineering and prototyping for an electromagnetic calorimeter are being sought from DOE within nuclear physics. The Argonne group, led by A. Yokosawa, has embarked on this phase of development for STAR. George Glass has been asked by John Harris, the spokesman of STAR, to join in this development effort. He has started to participate in the design of this calorimeter. The task ahead will require a serious engineering study with major

prototyping and testing. Further, a major effort is needed for simulation studies that would establish the detectability of the direct gammas and the associated jets within the plethora of tracks generated in the high luminosity environment anticipated for RHIC.

In the following section we describe in more detail our progress during the past three years on the LAMPF and TRIUMF N-N experiments, on the BNL rare kaon decay experiments, E871 and on the RHIC experiment, STAR. We will emphasize those experiments where analysis is in progress or has been completed, but for which the data have not yet been published.

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II. PROGRESS ON RESEARCH PROJECTS

A. N-N Elastic Measurements

Spin Transfer Measurements in np Elastic Scattering at LAMPF

A major goal at LAMPF has been to determine the nucleon-nucleon isospin-zero ($NN\ I=0$) phase shifts and amplitudes in the energy range 400-800 MeV. During the summer of 1990 we measured four isospin-transfer observables which, when combined with previous spin dependent data near 800 MeV, led to stable phase shift solutions[1]. In 1991 we obtained similar data at 485 and 635 MeV. These new experimental data allowed improvements in the phase shift analyses similar to that provided by the earlier 788 MeV data[2]. As recently as 1988 Arndt[3] had stated that above 500 MeV the $NN\ I=0$ phase shifts were "essentially undefined". Bugg[4] pointed out that the spin transfer observables K_{LL} , K_{SS} , and K_{NN} , in addition to the cross section and analyzing power, were needed to establish stable, well determined solutions, allowing the determination of the five complex scattering amplitudes. Since our experimental method measures K_{LS} simultaneously with K_{LL} and K_{SL} simultaneously with K_{SS} , we measured these four observables. This over determination also allows some cross-checking of possible systematic errors.

Nucleon-nucleon data bases and phase shift analyses are maintained by Arndt[5], Bugg[4], Bystricky, Lehar and Leluc[6], and by Hoshizaki[7,8]. With the inclusion of our new MeV data, the phase shift analyses show "an immense improvement" and are well determined with well behaved error matrices for the first time. Correlations in the error matrix have almost disappeared.

The E876 apparatus, shown in figure 1, is essentially the same as had been used in previous LAMPF experiments[9-11]. Polarized protons are focused onto a liquid deuterium target and neutrons, polarized by spin transfer, are collimated at zero degrees and directed onto a 15 liter liquid hydrogen target (the largest ever used at LAMPF). Scattered neutrons are detected in a large high-efficiency neutron detector. Recoil protons are detected in the Scylla spectrometer, which serves a dual purpose: 1) to measure the momentum and 2) to precess the recoil protons from L-spin to N-spin. Finally, the proton spin is analyzed in the Janus polarimeter.

During the summer of 1992 we used a different E876 configuration from that of the previous two years. The magnet Vartola replaced Scylla to allow for a horizontal bend instead of a vertical bend of the particles to measure K_{NN} , A_N and by extension, P for the reaction $np \rightarrow pn$.

Data were taken at 33 angles at 2 different energies: 788 MeV and 635 MeV, and at 30 angles at 485 MeV. The final results for K_{NN} and A_N have now been published[12,13]. The 788 MeV results are shown in figure 2. Final calculations of the polarization parameter P are in progress.

Figure 1: E876 detector system

Our analyses showed, unfortunately, that the energy dependent fit to A_{N0} diverges from the single-energy fits above 500 MeV, which may result from inadequate data at energies about 800 MeV, which influence the 800 MeV solutions by constraining the phases to follow smooth curves. Cross calibration would help to tie together the normalization of different data sets. By extending our analyzing-power measurements to forward angles, we should be able to tie together the normalization of the forward- and backward-angle peaks and also to tie the np- to the pp-normalization via quasifree measurements. Analyzing-power data are also a sensitive probe of the higher partial waves which are sensitive to isospin-0 inelasticity. For these reasons we wrote and submitted a second new proposal, "(np) Elastic Analyzing Power" (E1293). These measurements were carried out during the summer of 1993, and will be analyzed during the late fall of 1993. We measured analyzing powers at 485 and 788 MeV for $H(n,p)n$ and $H(n,pn)$ at laboratory angles of 30° , 35° , 50° , 55° , 60° , 65° , and 70° for 485 MeV and at these angles plus 25° , 40° , 45° , 47.5° , and 75° for 788 MeV. We

Figure 2: 788 MeV data for K_{NN} and A_{N0} obtained for E876 during the summer of 1992.

also carried out $H(n,d)$ measurements at 10° for 485 MeV and at 15° and 17.5° at 788 MeV in order to calibrate the angle settings from the deuteron reaction kinematics. Preliminary results indicate statistical precision better than 0.003 at most of these angles. The normalization is expected to be better than 2%, but this is yet to be determined since we have seen discrepancies from different data sets of runs around 3% where the statistics have been only $\sim 1\%$.

Our 1992 data [A_N , K_{NN} , and P], like our previous spin transfer data, have about an order of magnitude more statistical weight than the best previous data, and are in fact the most precise np data in the world. This high precision was made possible by the high intensity beam (up to 1 μ A average) from the optically pumped polarized source OPPIS. To summarize, near 500 MeV the data agree well with the previous data[14] and with recent analyses by Arndt[15] and Bugg[16]. Above 500 MeV these data are unique and complete the set of spin-dependent parameters needed to determine the scattering amplitudes.

The mixing parameter ϵ_1 determines the tensor force and the structure of the deuteron, and is strongly constrained by these new data. After including these data the uncertainty in ϵ_1 decreased by a factor of two. Arndt's and Bugg's solutions for ϵ_1 now agree within 0.5 degrees.

Our new data have also allowed us to resolve significant discrepancies between previous existing np data sets. The older TRIUMF data[14] disagree with more recent TRIUMF data[17], apparently as a result of an error in the angle calibration of the older data. Our new LAMPF data agree with the calibration of the more recent TRIUMF data within 0.1 degrees. The more recent TRIUMF data also disagree with the normalization of the older LAMPF data[18]. Our new LAMPF measurements, combined with last year's double scattering experiment, add considerable weight to the conclusion that the older LAMPF data were incorrectly normalized.

With the new data in place the isospin-0 phase shift solutions are becoming consistent for the first time. Arndt's single energy phase shift analysis (November 1992) now agrees to 1 degree with Bugg's. We expect to resolve the few remaining discrepancies in the coming year to complete the determination of the $I = 0$ nucleon-nucleon phase shifts and amplitudes up to 800 MeV.

LAMPF E1072 P-P Elastic Differential Cross-Section Measurements

E1072 measured pp cross-sections at 5 different energies (492, 576, 642, 728 and 793 MeV) from about 30° to 90° c.m. to an accuracy never before attempted[12]. The total uncertainty has been determined to be less than 1%, made possible by particle counting for beam normalization and extensive cross-checks of systematic effects. The new data are consistent with previous data above 600 MeV but have uncertainties of about a factor of 10 smaller. Near 500 MeV these data are consistent with 90° data from

but differ significantly from similar data from PSI. Figures 3 and 4 show our 492 and 576 MeV cross sections plotted against Bugg's and Arndt's fits.

With the inclusion of these new data Bugg and Bryan report stable solutions for the first time near 650 MeV for both isospin-0 and -1 and near 720 MeV for isospin-1 only. Near 800 MeV the phase-shift solutions agree for the first time with precise measurements of the pp total cross sections and with reasonable estimates for the pp-inelastic cross sections[19,20]. The latest phase shifts favor the values of VerWest and Arndt[19] over those of Bystricky *et al.*[20]. Subject to the limitation that phase-shift analyses average many discrete variables into smooth variables, we believe that these new data complete the determination of the isospin-1 amplitudes from 500 to 800 MeV, stabilizing the phase-shift solutions and providing an accurate calibration standard to which other data may be normalized.

Figure 3: 492 MeV pp differential cross section measured in E1072.

Figure 4: 576 MeV pp differential cross section measured in E1072.

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TRIUMF E372, Single Pion Production in np Scattering

Introduction

The process of pion production represents one of the simplest inelastic processes in the nucleon-nucleon system. It sheds light on the N-N and π -N interactions and is key to understanding pion production in more complex systems. Inelasticity accounts for over half the total N-N cross section above 1 GeV, rising quickly from threshold. Any model of the N-N system must be able to simultaneously describe elastic and inelastic scattering above and below pion threshold. In recent years, several such models have been proposed for the region 300–1000 MeV [1–8]. Most are coupled-channel models with long range pion exchange; the short range is described by heavier meson exchange with appropriate vertex functions, parameterized by cutoffs. Calculations have shown some agreement with the data, particularly for cross sections. Quantitative agreement remains elusive for many observables however.

All $NN \rightarrow NN\pi$ reactions are dominated at medium energies by the production of an intermediate resonant Δ which is the major contributor to cross sections. Nonresonant amplitudes may play a significant role, however, in spin observables which are strongly affected by interferences between partial wave amplitudes. For example, using a unitary three body model, Dubach, Kloet and Silbar showed in 1987 that nonresonant amplitudes, specifically those from the $T=0$ initial state, can have dramatic effects on their predictions for spin observables at 800 MeV, while having little effect on their cross section predictions [9]. The nonresonant amplitudes must be taken into account in any attempt to understand pion production except at energies near the Δ resonance.

The $np \rightarrow pp\pi^-$ and $np \rightarrow nn\pi^+$ reactions are best suited for studying the role of nonresonant amplitudes in the inelastic process because the $T=0$ initial state is available. The np system is an equal mixture of two isospin channels: $T=0$ and $T=1$. To conserve isospin, the Δ resonance ($T=3/2$) may proceed only from the $T=1$ initial state; at medium energies, other resonances ($\Delta\Delta$, N^* , etc.) are too far off-shell to have any effect on the reaction. Thus, all partial waves available in the $T=0$ channel represent nonresonant amplitudes. Furthermore, the $T=1$ channel can proceed via only the Δ^0 ($J=3/2$, $T=3/2$, $T_3=-1/2$) resonance, much weaker than the Δ^{++} which dominates in $pp \rightarrow np\pi^+$ and $pp \rightarrow d\pi^+$. The threshold for Δ production is 633 MeV, so an np reaction at 443 MeV ought to be particularly sensitive to nonresonant amplitudes.

Since the early measurements of pion production in the NN system, it has been clear that the $T=1$ channel is the dominant (and resonant) mode for pion production [10]. So strong is this channel, that many have wondered if there is any inelasticity at all in the $T=0$ channel. Almost all $np \rightarrow NN\pi^\pm$ measurements below 1 GeV have sought evidence for $T=0$ inelasticity, and often this was the principal motivation for doing the measurement. To understand how they went about this, it is necessary to briefly review

the formalism, as presented by Rosenfeld [11], used in discussing the isospin decomposition of $NN \rightarrow NN\pi$.

$NN \rightarrow NN\pi$ isospin formalism

All $NN \rightarrow NN\pi$ reactions can be described in terms of four independent cross sections which represent transitions from initial isospin states to final isospin states. These are listed below; the indices refer to the isospin of initial and final NN states, respectively. Note that there is no σ_{00} because that would violate conservation of isospin.

Isospin cross sections	Reaction cross sections
σ_{11}	$= \sigma(nn \rightarrow nn\pi^0) = \sigma(pp \rightarrow pp\pi^0)$
$\sigma_{11} + \sigma_{10}$	$= \sigma(nn \rightarrow np\pi^-) = \sigma(pp \rightarrow np\pi^+)$
$\frac{1}{2}(\sigma_{11} + \sigma_{01})$	$= \sigma(np \rightarrow nn\pi^+) = \sigma(np \rightarrow pp\pi^-)$
$\frac{1}{2}(\sigma_{10} + \sigma_{01})$	$= \sigma(np \rightarrow np\pi^0)$
$\frac{1}{2}(\sigma_{10}(d))$	$= \sigma(np \rightarrow d\pi^0)$
$\sigma_{10}(d)$	$= \sigma(nn \rightarrow d\pi^-) = \sigma(pp \rightarrow d\pi^+)$

Similar expressions for differential cross sections can also be written, but they are slightly more complicated [12]. The $NN \rightarrow NN\pi$ cross sections can be written in terms of transition amplitudes, such as those defined by Bystricky, *et al.* [13],

$$\begin{aligned}\sigma_{if} &= \left| \langle T_f T_{3f} \mid T_{3\pi} M \mid T_i T_{3i} \rangle \right|^2, \\ \sigma_{01} &= \left| \langle 1010 \mid M \mid 00 \rangle \right|^2 = \left| -\frac{1}{\sqrt{3}} M_{10} \right|^2, \\ \sigma_{10} &= \left| \langle 0010 \mid M \mid 10 \rangle \right|^2 = \left| M_{01} \right|^2, \\ \sigma_{11} &= \left| \langle 111 - 1 \mid M \mid 10 \rangle \right|^2 = \left| \frac{1}{\sqrt{2}} M_{11} \right|^2,\end{aligned}$$

where T_i, T_{3i}, T_f and T_{3f} refer to the isospin and projection for the initial and final state nucleons, and $T_{3\pi}$ is the isospin projection for the pion. (Note that the indices for Bystricky's amplitudes are opposite those for Rosenfeld's cross sections. To allow for comparison to the references, in this paper we use Rosenfeld's index ordering for the cross sections and Bystricky's index ordering for the amplitudes.)

Of relevance to $np \rightarrow NN\pi^\pm$ are the relationships

$$\begin{aligned}\langle pp\pi^- \mid M \mid pn \rangle &= -\langle nn\pi^+ \mid M \mid np \rangle = \frac{1}{\sqrt{6}} M_{10} + \frac{1}{2} M_{11}, \\ \langle pp\pi^- \mid M \mid np \rangle &= -\langle nn\pi^+ \mid M \mid pn \rangle = -\frac{1}{\sqrt{6}} M_{10} + \frac{1}{2} M_{11}.\end{aligned}$$

Exchange of the two initial state nucleons results in the M_{10} amplitude changing sign. Thus, if M_{10} is non-zero and at least partly in-phase with M_{11} , there should be a difference in these two cross sections, or equivalently, a forward-backward asymmetry in either one's differential cross section. If charge symmetry is invoked, a difference between $np \rightarrow pp\pi^-$ and $np \rightarrow nn\pi^+$ differential cross sections reveals the same interference.

Previous measurements of $np \rightarrow NN\pi^\pm$

Almost all of the previous measurements of $np \rightarrow NN\pi^\pm$ sought the $T=0$ effects by either (1) directly comparing $np \rightarrow NN\pi^\pm$ results to $pp \rightarrow pp\pi^0$ (pure σ_{11}) at the same energy, or (2) looking for asymmetries ($\pi^+-\pi^-$ or forward-backward) in differential cross sections.

Two papers [13, 14] have attempted to do global fits to all the known $NN \rightarrow NN\pi$ cross section data and calculate the resulting independent isospin cross sections by addition or subtraction. The results are far from satisfactory. A plot of all the published reaction cross sections for $np \rightarrow NN\pi^\pm$ below 1 GeV [15–25] is shown in figure 1. Also shown is Arndt's estimate for $\frac{1}{2}\sigma_{11}$ based on measured cross sections for $pp \rightarrow pp\pi^0$ up to 1 GeV. Except for some possibly interesting data points at ~ 600 – 650 MeV, the np cross sections appear to fall along the $\frac{1}{2}\sigma_{11}$ curve. From this evidence, Arndt estimates that the $T=0$ inelasticities are essentially zero below 1 GeV. Bystricky, on the other hand, argues that the $T=0$ inelasticity is not negligible below 1 GeV. Both papers point out the need for better cross section data, and more data for $np \rightarrow np\pi^0$ (which acts as a constraint on the other cross sections). What can be learned from these summaries is that the $T=0$ cross section is small, if nonzero, and that total cross section measurements are not sensitive enough to reveal it.

Figure 1: Total cross sections for $np \rightarrow NN\pi$ below 1 GeV

There is no similar summary which looks for the $T=0$ in all the differential cross section data. However, it is interesting to note that most of the published $np \rightarrow NN\pi^\pm$ experimental papers claim to see $T=0$ in their data. For example, Yodh [15] and Handler [18] agree in their claims to see a forward-backward asymmetry at 409 MeV. Kleinshmidt [22] found an angular distribution for the charged pions that was different than the corresponding distribution for $pp \rightarrow pp\pi^0$. Thomas [23] found a difference in the energy spectra between π^+ and π^- for some pion angles. Despite these various claims there has been no trend that shows the nature of the $T=0$ channel, and so its role in pion production remains elusive. As such, the inelasticity in $T=0$ is usually considered negligible for phase shift analysis below 1 GeV [26].

There have been few measurements of spin dependent observables for $np \rightarrow pp\pi^-$, mostly because of the difficulty in obtaining a polarized neutron beam of high quality. Ponting [27] measured the 400 MeV analyzing power (A_{NO}) of the quasi-free reaction $p+d \rightarrow (p)+\pi pp(^1S_0)$, where the (p) refers to the spectator proton and the (1S_0) refers to the fact that the experiment was sensitive only to events with the protons in a relative 1S_0 ($L_{pp}=0$) state. The results of that experiment served to clarify the relative importance of the various partial waves which feed this final state. Terrien *et al.* [28] made measurements of the analyzing power at beam energies of 572, 784, 1012 and 1134 MeV. In Terrien's measurement, the analyzing powers were calculated in bins of invariant p-p mass and pion CMS angle. They used a 4π detector so these results represent weighted integrals over the remaining phase space variables. The relative efficiency of their detector is not known. In this paper, we report similar measurements of A_{NO} and A_{SO} , as well as relative $d\sigma/d\Omega$ for a neutron beam energy 443 MeV. We will discuss how the nonresonant amplitudes (in both $T=0$ and $T=1$ channels) affect these observables later in this paper.

The Experiment

The experiment was performed at the TRIUMF cyclotron using the polarized neutron beam facility. The neutron beam was collimated on a liquid hydrogen target and the subsequent reaction products (protons and pions) measured in large acceptance drift chambers and a cylindrical array of scintillator bars. The directions, times-of-flight and pulse heights were measured for the charged particles and kinematic events reconstructed based on this information. Yields and asymmetries were extracted and binned as functions of various coordinate variables. Full experimental details can be found in reference [29], but an overview of the important details are given here.

The beam

A schematic drawing of the E372 beamline at TRIUMF is shown in figure 2. The polarized neutron beam is created by scattering polarized protons from a liquid deuterium production target. We used an optically pumped polarized ion source (OPPIS) which provided us with an intense beam ($\sim 10\mu A$) of polarized protons with

typically 45–50% polarization [30]. We were the first users of OPPIS; for later experiments, the polarization improved dramatically. A special tuning procedure, which consisted of stripping slits placed in the cyclotron and harmonic bunching, provided a narrow, pulsed 457MeV proton beam of 450ps FWHM every 43 nanoseconds [31]. The status of this tune was monitored at all times by a fast response monitor in the proton beam which measured the centroid and width of the proton bursts and relayed this information to the cyclotron control center every two minutes. The tuning procedure had less than 10% transmission and the proton intensity at the LD2 target was typically 500nA which resulted in approximately 1 million neutrons per second at our target, 12.6m downstream. The tightly bunched beam allowed for clean extraction of the quasifree 443MeV neutrons from the inelastic neutral background. The time structure of the beam is shown as in insert at the bottom right of figure 2. The neutron beam energy was known to within ± 3 MeV, with very little contamination from inelastic neutrals.

The 457MeV proton beam passed through two proton polarimeters then through a superconducting, solenoidal magnet (JANIS) which precessed the polarization from normal to sideways. The quasifree reaction $p+d \rightarrow np+(p)$ has a spin transfer coefficient, $K_{SS} = -.8066$ and $K_{SL} = -.0125$ at 9° for 457MeV incident protons [32], so neutrons exiting at 9° had polarizations of typically 32–35% in the sideways direction. Behind the LD2 production target was a large sweeping magnet which swept away charged particles and precessed the neutron polarization by 21.3° . The neutrons at 9° were collimated by a steel and lead collimator then passed through two dipole precessing magnets (CLYDE, BONNIE). The currents of these magnets were set to produce a net neutron polarization in S, N or L. Behind these magnets was the liquid hydrogen target and experimental detectors. Further downstream was a neutron profile monitor which was used to ensure that the neutron beam was aimed directly at the LH2 target. Also in the neutron beam were two neutron polarimeters. Neutron beam polarization in all directions (P_x, P_y, P_z) was calculated as a function of the proton polarimeters and magnet settings, then checked against the neutron polarimeters. Agreement among all polarimeters was excellent, well within the precision of all polarimeters. Uncertainty for transverse polarization is estimated at $\sim 3\%$; uncertainty in the L-type beam is slightly higher because the neutron polarimeter cross check was not available. As a further check, we calculated the analyzing power for a subset of $np \rightarrow np$ events in our experimental detector. The result compared with Arndt's phase shift solution [33] is shown in figure 3. Agreement is very good. Although error bars are statistical only, some systematic uncertainties creep in for large neutron angles because the np elastic signature was not as clearly identifiable for those angles. The beam polarization was flipped every two minutes and turned off for one minute. One drawback to the neutron beam was that the neutron polarization varied greatly over the course of the runs, ranging from 0.26 to 0.35 (a 28% variation). This required that asymmetries be extracted carefully and is discussed more fully later.

Figure 2: E372 Beam Line

Figure 3: Analyzing power for np elastic scattering

The experimental setup

Figure 4 shows a diagram of the target and detector. The target was liquid hydrogen contained in a 5mil mylar flask. The flask was 5cm diameter, 16cm high. It sat in a specially designed vacuum chamber which had large exit windows at the entrance and sides made of 5mil mylar. A large downstream window was constructed of 3mil kapton and 8mil kevlar—most of the charged particles passed through this window. We took approximately 25 million events to tape, about 1/3 of which was with the target empty.

The detector was built around the known kinematics of $np \rightarrow pp\pi^-$ at 443MeV. At this energy, the protons are constrained to be emitted within a lab angle of 42° . Two large drift chambers and a scintillator hodoscope array (S_1 and S_b) measured the directions and velocities of the charged particles. From this information, the kinematics of each event could be reconstructed. For three-track events (the situation where the pion goes forward into the detector) there is little background competition, since there are few neutron induced processes that can produce three charged particles in the final state. Acceptance for these events is limited, however, to the case where three separate bars are hit. For two-track events, there is considerable competition from quasifree $nn \rightarrow np\pi^+$ events originating in the target walls, vacuum windows and timing scintillator, S_1 . Nevertheless, good kinematic analysis was able to reject most background events for both two-track and three-track events. Good $np \rightarrow pp\pi^-$ events represented less than 3% of the total data analyzed, or roughly 400,000 usable events over N, S and L states. In addition to these two major components, were various

calibrating devices: small "button" scintillators which sat behind the scintillator bars, small axial detectors which were accurately placed in the center of the beam axis, two side MWPCs for detecting backward going pions. These devices were associated with their own triggers which could override the main trigger and were used to pinpoint and simplify calibrations. There was also a thin wire counter (TLD) which sat directly between the S_1 counter and the target. This detector was designed to ensure that charged particles originated from the target region.

$$\text{Trigger: } S_1 \cdot S_{\text{bar}} \cdot S_{\text{bar}} \cdot (\overline{S_{\text{veto}}})$$

Figure 4: Experimental apparatus for TRIUMF for E372

The event trigger for the experiment consisted of three levels: 0, 1, 2. At the base level, a trigger consisted of a pulse from a single photomultiplier in any bar. This provided the common "start" for all TDCs and the "stop" for the drift chamber electronics. The level-1 trigger is shown in figure 5. It required that (1) the computer be ready for data, (2) a second bar have fired, (3) the S_1 have fired, (4) the TLD fired and (5) no VETO. A crude pattern recognition which vetoed events for which only the upper or lower bars fired was also included. If the level-1 condition was not fulfilled, a fast clear was sent to all electronics and all registers cleared. The level-2 trigger was a software trigger written in the J11 ("Starburst") preprocessor which was responsible for buffering the data and sending it to the acquisition computer (a VAX 750) for spooling on to 8mm

tape. This trigger required that (1) the event time with respect to the RF correspond to the neutron pulse, (2) the events were not from the central regions of the two center bars, and (3) there were more than 12 wire chamber hits registered. These cuts in the trigger were designed to eliminate γ induced events or single track events which mimicked a 2-track event by double scattering through two adjacent bars. The J11 preprocessor buffered the variable length events (typically 340 bytes each) in its 16K memory, then dumped the buffer to the VAX 780. The buffering was done at a rate of about 2ms per event; the dumping took about 100ms. Event collection was typically 140 Hz, limited by acquisition speed. We ran at typically 40-50% dead time.

Figure 5: Level-1 trigger

The scintillator array provided timing and pulse height information. The array consisted of 18 NE104 plastic scintillator bars, each $200 \times 10.4 \times 3 \text{ cm}^3$, in a curved array 120cm from the target. The bar at the very top and the bar at the very bottom were of slightly different thicknesses. Each bar was viewed at both ends by TRIUMF standard Phillips XP2230 phototubes. The usual optimizing of the system (gain matching, voltage plateauing, *etc*) was done. Software calibrations were based on np elastic data where the kinematics are fully constrained. Conversions from TDC and ADC units to standard units (nanoseconds, MeV) were found through extensive calibrations and revealed that the system had better than $\sigma=240\text{ps}$ timing resolution, and $\sigma=3\text{MeV}$ energy resolution for all bars. The time difference between a bar and S_1 provided velocity information; the pulse height information helped in particle identification and acted as a further constraint in the kinematic reconstruction. Figure 6 shows a plot of raw time-of-flight (TOF) versus the position along bar 13 (top); the bottom of the figure shows velocities plotted vs. energy loss. The correlation follows the expected Bethe-Bloch relationship at proton kinetic energies greater than 70MeV; the leading edge of the distribution represents protons which stopped in the bars and deposited all their energy. Proton and pion events are identifiable by inspection.

Figure 6: Time-of-flight, Energy Loss

The tracking detector consisted of two large drift chambers, with active areas of $59.5 \times 22.0 \text{ in}^2$ and $59.5 \times 42.0 \text{ in}^2$. We ran with a gas mixture of 50/50 argon/methane, bubbled through a 0° alcohol bath. Each chamber had six sense planes with wires running in the following coordinate directions: UYXXUY. The "U" direction is 45° to X and Y and helped resolve the ambiguities created by multiple tracks. The sense wires were made of 1mil. gold-plated tungsten and were 2 inches apart connected to individual preamps, discriminators and TDCs. Typical voltages were -2200V and -3200V for the field-forming wires and foils respectively. Drift resolution was $\sim 0.6\text{mm}$; the efficiency per plane was typically 96%. The drift times were read and encoded using LeCroy 4290 digitization electronics and the data words appended to the end of the event buffer.

Track reconstruction through the detector turned out to be the most difficult and most CPU intensive aspect of the analysis. Multiple tracks through the detector gave rise to problems of high combinatorics, especially with events that had cross-talk. Furthermore, the large cell size (2 inches) resulted in many tracks sharing cells and making them difficult to resolve. Traditional pattern recognition approaches based on histogramming-cluster searches and "track road" methods were attempted but found to be unsuitable. An approach using template matching followed by full combinatoric fitting proved to be workable. In this method, a set of templates recording all the possible cell patterns which correspond to physical tracks is stored as an indexed list in memory. A measured pattern is compared to the list and the best candidates are kept. After this initial screening, least squares line fitting is done to all the drift ghost combinations per candidate to find the best tracks. Single track efficiency was $\sim 98\%$. Cleanly separated multiple tracks had typical efficiencies of $\sim 89\%$ for two tracks, $\sim 85\%$ for three tracks. However, multiple-track efficiency overall was lower because it depended on the relative angles of the tracks and the cuts applied in the tracking algorithms. Vertices were calculated for multiple tracks and found to have RMS deviations of less than 1.03cm for 67% of the multiple-track events. The layout and performance of the drift chambers are indicated in figure 7 (top). The bottom of the figure shows a plot of vertices for an empty target run (for $\sigma_{\text{vertex}} < 1.0\text{cm}$).

Raw events were written to 8mm tape for storage and later reduction. Data tapes were read by analysis routines which converted the raw data words into physical quantities such as times-of-flight, energy loss, tracks and kinematics. Cuts were applied based on kinematic criteria designed to select only $np \rightarrow pp\pi^-$; the resulting data were binned in appropriate ways. A few details of the analysis are presented below.

E372 drift chambers

Wire chamber parameters:

Small active area: 151.1 cm x 55.9 cm

Large active area: 151.1 cm x 106.7 cm

Chamber gas:
50/50 argon/methane + 1% alcohol

Cell size: ± 1 inch

Plane efficiency: $\sim 96\%$

Voltages: -2200V wires, -3200V foils

Figure 7: E372 drift chambers (top), drift chamber performance (center), vertex reconstruction (bottom)

Event Analysis

Reconstructing kinematics

The kinematics for each event were determined from the measurements of track angles, times-of-flight, and energy loss in the bars. For three-track events, conservation of energy and momentum are sufficient to accurately calculate the kinematics based on angles alone. For two track events, the kinematic reconstruction technique is indicated schematically in figure 8. To summarize, a kinematic χ^2 was defined by

$$\chi^2(p) = \frac{(TOF_1 - tof_1)^2}{\sigma_{TOF}^2} + \frac{(TOF_2 - tof_2)^2}{\sigma_{TOF}^2} + \frac{(dE_1 - de_1)^2}{\sigma_{dE}^2} + \frac{(dE_2 - de_2)^2}{\sigma_{dE}^2}.$$

Here, the upper case variables (TOF , dE) represent the measured quantities; the lower case variables (tof , de) represent the estimated quantities which depend of the adjustable parameter p . p is the momentum of one of the tracks. The first choice for p was determined based on a time-of-flight and a guess of the particle's identity. The rest of the kinematic variables were determined by solving for a second momenta *via* the quadratic

$$p_2 = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A},$$

where the following quantities are defined,

$$\begin{aligned} A &= \frac{((\vec{p}_{lab} - \vec{p}) \cdot \hat{e})^2}{(E_{lab} - E)^2} - 1, \\ B &= \frac{(m_2^2 - m_3^2 + (E_{lab} - E)^2 - |\vec{p}_{lab} - \vec{p}|^2)((\vec{p}_{lab} - \vec{p}) \cdot \hat{e})}{(E_{lab} - E)^2}, \\ C &= \frac{(m_2^2 - m_3^2 + (E_{lab} - E)^2 - |\vec{p}_{lab} - \vec{p}|^2)^2}{4(E_{lab} - E)^2} - m_2^2, \end{aligned}$$

$E_{lab}, \vec{p}_{lab}$ = total lab energy and momentum,

$E, \vec{p}$ = given particle's energy and momentum,

$\hat{e}$ = unit vector of second track direction.

After the kinematics for a particular p were determined, the particles were "propagated" through an imaginary detector designed to mimic the effects of the actual

- Three body final state has 5 degrees of freedom
- Six angles: kinematics completely constrained
- Four angles and one velocity: kinematics partially constrained

Two-track events (four angles, two TOFs)
required minimizing a kinematic χ^2 .

$$\chi^2 = \frac{(t_{\text{obs}} - t_{\text{expected}})^2}{\sigma_{\text{TOF}}^2} + \frac{(t_{\text{obs}} - t_{\text{expected}})^2}{\sigma_{\text{TOF}}^2} + \frac{(\Delta E_{\text{obs}} - \Delta E_{\text{expected}})^2}{\sigma_{\Delta E, \text{bar}}^2} + \frac{(\Delta E_{\text{obs}} - \Delta E_{\text{expected}})^2}{\sigma_{\Delta E, \text{bar}}^2}$$

Figure 8: Kinematic Reconstruction Technique

detector. The resulting times-of-flight and energy losses (tof , de) were input in the χ^2 defined above. This process was repeated for different p until the χ^2 was minimized. Minimization was typically done in 3 to 6 iterations. However, the quadratic expression has two solutions and there are three unknown particle identities, so the minimization was repeated six times for each solution and each particle combination. In the end, we were left with the kinematics and particle identities which best suited the experimental measurements.

It is clear that this χ^2 minimization depended strongly on our ability to mimic the detector in software. Extensive calibrations were done on the tof and de routines to ensure that they were accurate. The results shown in figures 9a and 9b suggest that this χ^2 technique was both accurate and effective. In figure 9a (top half of figure), we show the vertex reconstruction for events with good reduced χ^2 (<1.0) and those with poor reduced χ^2 (>3.0). It is clear that the poor χ^2 are correlated with the walls and background materials, as we would expect for events which come from bound protons in carbon that have a lot of Fermi motion. Good χ^2 are correlated with the free hydrogen. In figure 9b (bottom half of figure), we show the result of the particle identification (which comes out the kinematic minimization). The two-track events which reconstructed as πp events are strongly correlated with the target walls and background. This is consistent with the hypothesis that the background is mostly $nn \rightarrow np\pi^-$ which has a large cross section ($nn \rightarrow d\pi^-$ was also seen, but event reconstruction did not explicitly solve for it). On the other hand, pp events are strongly correlated with the LH2 region. The final cut on the data was the following: (1) at least two protons, (2) $\chi^2/N < 2.0$, and (3) $r_{xz} < 2.5\text{cm}$. Over 97% of the data failed this series of cuts. For target empty runs, almost no events satisfied the cuts. Comparison between equal amounts of beam for full and empty runs (corrected for live time) revealed a 22:1 signal to noise ratio.

Estimating observables

The event analysis resulted in a very clean set of data of good kinematic accuracy. However, the long and tortuous path leading to the final data set had a strong effect on the acceptance over phase space that is difficult to estimate. A series of Monte Carlo simulations were performed and subjected to the same analysis as the actual data. From this, two efficiency functions were found, one for the two-track events and one for the three-track events. Since these classes of events were analyzed differently, their efficiency functions were different. Events were binned and corrected using these functions. The resulting relative differential cross sections for the two-track and three-track events matched over phase space regions where both efficiency functions were reliable. In some regions however, an efficiency function would drop dramatically and become very small. In these regions, the two- and three-track relative cross sections did not always match. In such cases, the cross section corresponding to the more reliable correction function was chosen as correct. Thus, for this measurement, the efficiency and the actual acceptance are not the same quantity. The resulting relative differential

Figures 9a (top), 9b (bottom): Kinematic cuts

cross sections show no strong discontinuities. Statistical error is small; the error bars are estimates of systematic errors which result from uncertainty in the correction functions.

Asymmetries were calculated from the data set and are of much higher quality than the differential cross sections. The main reason is that no correction function has been applied. The probability of detecting an event is defined in terms of the analyzing power and beam polarization (P) as

$$p(\bar{\rho}, \phi, \bar{P}) = \left(\frac{d\sigma}{d\rho} \right) \varepsilon(\phi) \varepsilon(\bar{\rho}) \varepsilon(\bar{P}) \left[1 + A_{SO} P \cos(\phi_P - \phi) + A_{NO} P \sin(\phi_P - \phi) + A_{LO} P_z \right],$$

where

$d\rho$ = an element of phase space (not including ϕ),

$\varepsilon(\phi), \varepsilon(\bar{\rho})$ = detection efficiencies at ϕ and $\bar{\rho}$,

$\varepsilon(\bar{P})$ = the probability that the beam has polarization $\bar{P}$,

and the angles are defined in figure 10a. This expression assumes negligible background. This equation is similar to those given by other authors (see Shypit [34], for example), except that this expression is valid for beam polarizations and analyzing powers in arbitrary directions. For A_{LO} , we calculated an asymmetry between yields for longitudinal polarization “normal” and “reverse.” This technique is less than ideal since systematic errors may come in from non-zero transverse components in the beam polarization. The relative systematic error for A_{LO} is estimated at 1%–2%. For the transverse polarizations, we maximized the likelihood function which corresponds to the above probability in terms of parameters A_{NO} and A_{SO} , solving for both simultaneously. This was accurate to second order under the assumption that the detector is symmetrically efficient, *i.e.*, $\varepsilon(\phi) = \varepsilon(\pi - \phi)$, or that the net beam polarization averaged to zero. Both of these conditions were satisfied for our experiment, and this is supported by the fact that $A_{NO} = 0$ where it should be. The A_{NO} of figure 4 was calculated by this technique. We used this approach because it allowed us to calculate A_{NO} and A_{SO} from the data event by event without binning in terms of ϕ , and correctly treated the fact that the beam polarization varied over the course of several runs. Error bars quoted for transverse asymmetries represent statistical uncertainties at the 67% probability limits. Error bars for A_{LO} include estimates of systematic uncertainty folded in.

Figure 10a: Azimuthal definitions

Figure 10b: Coordinate systems defined for NN->NN π reactions

Results and Discussion

The observables are presented in terms of four kinematic variables: M_{pp} , $\cos\theta$, $\cos\psi$, χ , which are illustrated in figure 10b. The scattering plane azimuthal, ϕ , serves only to rotate the reaction frame with respect to the lab frame, and so is not inherently interesting. M_{pp} is the invariant mass of the p-p system. The angular variables are independent and represent equally accessible phase space in the absence of any physics. θ and ϕ are the polar angles of the pion in the center-of-mass system. The variables ψ and χ are polar angles defined for the fast proton in the decay frame of the p-p system; $\cos\psi$ has range 0–1.

Differential cross sections

Relative differential cross sections, projected to a single variable, are shown in figure 11. We have normalized our data to a total cross section of 0.1mb, which was estimated from the curve on figure 1. Also shown are predictions of Kloet and Lomon [7] based on T-matrices provided to us (dashed line). The dotted line is a pure phase space prediction; the dotted-dashed line is the effective efficiency function. We find a strong $\cos^2\theta$ dependence, as did Kleinshmidt and Thomas at higher energies. This can be fit to a polynomial of the form $d\sigma/d\Omega \sim 1/3 + bx^2$, where $b=0.47 \pm 0.06$.

Analyzing powers

Projected analyzing powers as functions of angular variables and p-p invariant mass slices are shown in figure 12-14. To conserve parity, A_{SO} and A_{LO} projected to θ and ψ are expected to be zero, and are also measured to be zero. Thus, these results, which are not shown, serve to act as a check on our analysis. The solid curves are predictions from Kloet and Lomon. Agreement is reasonable except for the predictions of A_{NO} projected to θ . Also shown are the results of some partial wave interferences to demonstrate the effects of different partial wave amplitudes in these observables. We discuss these partial waves below.

Figure 11: Relative differential cross sections for $np \rightarrow pp\pi^-$ at 440 MeV

Figure 12

Figure 13

Figure 14

Figures 12-14: Projected $np \rightarrow pp\pi^-$ analyzing powers as functions of angular variables and p-p invariant mass slices. From parity conservation, A_{SO} and A_{LO} projected to $\cos\theta$ and $\cos\phi$ are expected to be zero. The dotted lines show the Kloeit-Lomon predictions

Discussion

Observables can be understood in terms of helicity amplitudes [35]. Let $M_{\pm\pm}$ be the amplitudes for beam and target spins $\pm\frac{1}{2}$ in the beam direction. Since the spins of the final state nucleons are unobserved, we suppress their indices and imply a summation over final spins. The unpolarized cross section is given by

$$4\sigma = \text{Tr}(M^\dagger M) = |M_{++}|^2 + |M_{+-}|^2 + |M_{-+}|^2 + |M_{--}|^2$$

and the analyzing powers by

$$4\sigma A_\alpha = \text{Tr}(M^\dagger \sigma_\alpha M),$$

where σ_α is the Pauli spin operator and operates on the beam particle only. The explicit results are:

$$\begin{aligned} 4\sigma A_x &= 2 \text{Re}(M_{++}^\dagger M_{-+} + M_{--}^\dagger M_{+-}), \\ 4\sigma A_y &= -2 \text{Im}(M_{++}^\dagger M_{-+} - M_{--}^\dagger M_{+-}), \\ 4\sigma A_z &= |M_{++}|^2 + |M_{+-}|^2 - |M_{-+}|^2 - |M_{--}|^2. \end{aligned}$$

The amplitudes M can be written as a linear combination of partial waves which represent transitions from initial angular momentum states to final angular momentum states. The partial waves are defined in terms of seven quantum numbers: S, L, J, S', L', J', l . The numbers refer to: (S) the initial spin state, (L) the initial orbital angular momentum, (J) the total angular momentum, (S') the spin state of the final two nucleons, (L') the relative orbital angular momentum of the final two nucleons, (J') the total angular momentum of the final two nucleons, (l) the orbital angular momentum of the pion with respect to the nucleon system. In spectroscopic notation, the numbers are written like so: $2S+1L_J \rightarrow (2S'+1)(L')(J')(l)(J)$, as for example ${}^3S_1 \rightarrow {}^3P_1 s_1$.

Not all angular momentum transitions are allowed, and not all partial waves are included in each amplitude. For example, for $np \rightarrow pp\pi$, ${}^3S_1 \rightarrow {}^3P_1 s_1$ is allowed, but ${}^3S_1 \rightarrow {}^3S_1 s_1$ is not because it violates parity invariance. Neither wave would be included as a M_{++} or M_{--} term because they are singlet initial states and cannot form a $(++)$ or $(--)$ state. A list of partial waves which conserve isospin, angular momentum, parity, and which respect the symmetry of the final state protons is given in table 1. The table is limited to partial waves with small final state orbital angular momenta (waves with $L'+l_\pi < 2$). Due to the small amount of CMS energy available to the final state particles (70 MeV for this experiment), higher partial waves are suppressed by the centrifugal barrier.

	$T = 0$	$T = 1$
$l_\pi = 0$	${}^3S_1 \rightarrow {}^3P_1 s_1$ ${}^3D_1 \rightarrow {}^3P_1 s_1$ ${}^3D_2 \rightarrow {}^3P_2 s_2$	${}^3P_0 \rightarrow {}^1S_0 s_0$ ${}^1S_0 \rightarrow {}^3P_0 s_0$ ${}^1D_2 \rightarrow {}^3P_2 s_2 (*)$ ${}^3P_2 \rightarrow {}^1D_2 s_2$ ${}^3F_2 \rightarrow {}^1D_2 s_2 (*)$
$l_\pi = 1$	${}^3S_1 \rightarrow {}^1S_0 p_1$ ${}^1P_1 \rightarrow {}^3P_0 p_1, {}^3P_1 p_1, {}^3P_2 p_1$ ${}^3D_1 \rightarrow {}^1S_0 p_1$ ${}^1F_3 \rightarrow {}^3P_2 p_3$	${}^3P_0 \rightarrow {}^3P_1 p_0$ ${}^3P_1 \rightarrow {}^3P_0 p_1, {}^3P_1 p_1, {}^3P_2 p_1$ ${}^3P_2 \rightarrow {}^3P_1 p_2, {}^3P_2 p_2$ ${}^3F_2 \rightarrow {}^3P_1 p_2, {}^3P_2 p_2$ ${}^3F_3 \rightarrow {}^3P_2 p_3$
$l_\pi = 2$		${}^3P_2 \rightarrow {}^1S_0 d_2$ ${}^3F_2 \rightarrow {}^1S_0 d_2$

(*this wave can go through the intermediate resonant state, $N\Delta$).

Inspection of the partial waves and the definitions for observables allows us to make some generalizations. It is clear that the analyzing powers are sensitive to interferences between partial waves. Furthermore, interference can only occur between amplitudes with the nucleons in the same final spin states, and there must be a contribution from a triplet wave. For observables integrated over nucleon final states, only those with the same N-N final state angular momentum will survive.

Generally, the total amplitude is written as a sum of the individual partial wave amplitudes like

$$M = \sum_{k=1}^{\infty} \eta_k e^{i\varphi_k} F_k,$$

where each wave (k) has a characteristic inelasticity (η), phase shift (φ), and angular momentum decomposition (F) which contains the spherical harmonics, Clebch-Gordon coefficients, and Wigner rotation matrices $d_{m'm}^j$. A full analysis of spin observables in terms of partial waves requires a careful and detailed fitting procedure to all known data, with theoretical input where appropriate. However, we can get some insight to the roles of the partial waves by looking at the effects of simple interferences between selected waves.

If we allow only two waves (*i.e.*, set $\eta=0$ for all but two, and set their phases such that $|\varphi_a - \varphi_b| = 90^\circ$), we can look at their effects. An example of this for A_{NO} projections to $\cos\theta$ is shown in figure 15. In this way, we can let our results point us towards possible amplitudes.

Figure 15: Predictions of ANO vs. $\cos\theta$ for lowest partial wave interferences. Protons must be in the same final state to have non-zero values. For this diagram, the relative phase of the partial waves were set to 90° degrees.

Conclusions

We have measured the relative differential cross section and first spin observables for the reaction $np \rightarrow pp\pi^-$ at 443 MeV. Some conclusions are:

1. The relative differential cross section reveals a $\cos^2\theta$ dependence. The form of the fit is $d\sigma/d\Omega \sim 1/3 + bx^2$, with $b = 0.47 \pm 0.06$. As Kleinschmidt found, this varies from published results of $pp \rightarrow pp\pi^0$ which give $b \sim 0.0$. Newer, unpublished results give b for $pp \rightarrow pp\pi^0$ to be non-zero [36]. Consequently, it is difficult to say with certainty that the shape of $np \rightarrow pp\pi^-$ differs from that of $pp \rightarrow pp\pi^0$.
2. The p-p invariant mass distribution peaks slightly at small masses. This could be due to either a 1S_0 final state interaction (FSI) or an enhancement from π -p when the pion has greater energy, and thus is more likely to be in a relative p-state with a proton. A 1S_0 final state interaction would probably show a stronger, narrower peaking than what we observe. Our invariant mass resolution is on the order of ~ 6 MeV, so the peak may be washed out slightly.
3. Measurements of A_{NO} show all-negative values over the pion CMS angle, θ . This reflects the interference of waves from s-state and p-state pions. Interferences of s-wave pions only, p-wave pions only, or s-wave with d-wave pions will all give values of A_{NO} which cross the axis. Interference can only occur with the final state protons in the same spin and angular momentum state (for this observable and kinematic variable). Looking at the available waves, this suggests that partial waves of type Ps and Pp are required. It was hoped that only Ss, Sp and Ps waves would be necessary to explain the data. In such a restricted case, one could hope to determine the $I=0$ partial waves responsible for single pion production. Since there are so many Pp waves available, more observables are necessary to identify uniquely the roles of each wave.
4. Measurements of A_{SO} shows a $\sin 2\chi$ behavior in general. However, it seems clear that the asymmetries do not cross the axis at 90° as must be the case for interference between only two partial waves. At least three partial waves must interfere, producing a $\sin \chi$ term and a $\sin 2\chi$ term to result in the observed crossings at $\sim \pm 50^\circ$.
5. Measurements of A_{LO} are non-zero and very interesting. A low p-p mass, they show a generally $\sin \chi$ dependence, whereas at higher p-p masses, a $\sin 2\chi$ dependence appears. This behavior is very useful in eliminating various partial wave candidates. More A_{LO} measurements would be warranted in future studies of this reaction.
6. Agreement for some observables with the predictions of Kloeet and Lomon is interesting and encouraging. Although their model is not designed to predict accurately pion production near threshold, it is clear that our data can and does critically test such production models.

7. More spin observables for this reaction (and the $I=1$ reaction, $pp \rightarrow pp\pi^0$) should be made. Many measurements of total cross section and one- and two-dimensional differential cross sections have been attempted with confusing or conflicting results. Most measurements of $np \rightarrow pp\pi^-$ have attempted to reveal $I=0$ effects by looking for an obvious signature of the form (1) a total cross section which differs from that of $pp \rightarrow pp\pi^0$, (2) a differential cross section which differs in shape from that of $pp \rightarrow pp\pi^0$, or (3) a forward-backward asymmetry in the pion differential cross section. For such signatures, $I=0$ amplitudes must be either large or in-phase with $I=1$ amplitudes. Spin observables are sensitive to specific partial wave amplitudes and require waves to be out of phase. Our measurements reveal that several waves are necessary, and suggest that the $I=0$ question will most likely be resolved by a careful and detailed analysis of many spin observables.

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C. LAMPF E1097, Single pion production in np scattering

Overview

In recent years, there has been a major effort in both the experimental and theoretical investigation of the coupled $NN\text{--}NN\pi$ problem. This set of reactions is one of the simplest inelastic processes available for study. It sheds light on the NN and $N\pi$ interactions and is key to understanding pion production in more complex systems. There are four independent channels available in the $NN\text{--}NN\pi$ reaction. These channels can be expressed in terms of the total isospin of the initial (I) and final (I') state nucleons (I, I'): (1,0), (1,1), (0,1), (0,0). The dominant channel for pion production is through the (1,0) resonance, since the famous Δ^{++} ($I=3/2$, $P=3/2$) can proceed through this channel. The role of the non-resonant amplitudes, particularly the (0,1) channel, remains elusive. The reaction $np \rightarrow pp\pi^-$ may proceed through the (1,1) and (0,1) channels, which avoid the Δ^{++} , making it an ideal reaction for studying the non-resonant contributions to pion production. The reaction is experimentally accessible, since all final state particles are charged, allowing efficient and precise determination of all outgoing trajectories.

LAMPF Experiment 1097 proposed to measure the differential cross section, σ , and the spin observables A_{NO} , A_{LO} , A_{SO} , A_{OL} , A_{SL} , A_{NL} , and A_{LL} for the single pion production reaction $np \rightarrow pp\pi^-$ at neutron beam energies in the range 500–800 MeV. It was planned to run E1097 in two separate phases. Phase I, which was planned for 1993, was to use a polarized neutron beam and a liquid hydrogen target; Phase II, expected to run in 1994, was to use a polarized frozen spin hydrogen target to enable the spin correlation parameters to be measured. In August, 1992, 500 hours of beam at 800 MeV were approved for Phase I of the experiment. The Phase I measurements were to be the same as those of TRIUMF E372 at lower energy (438 MeV), and many of the E372 collaborators also participated in E1097. In what follows we will describe our E1097 detector development efforts of the past three years.

Detector System

Figure 1 shows the primary component of the E1097 detector apparatus, the cylindrical wire chamber, with the LH2 target at the center. The chamber, about 1 meter long with a 30 cm radius, has a vertical acceptance of $\pm 60^\circ$ and a horizontal acceptance of up to $\pm 180^\circ$, and should detect all three final state particles for more than 50% of phase space. Each of the 448 sense wires of the detector, divided into 8 cylindrical planes, measures a particle track's perpendicular distance from the wire via drift time, while determining the distance of the track along the wire through charge division. Thus, we must read the charge from each end of the wire with ADC's, while timing these pulses relative to the start of the event with a TDC.

Figure 1: E1097 Experimental Detector

The second element of the detector system consists of a thin, curved scintillator (S1), mounted between the target and wire chamber, and a large array of 21 vertical scintillator bars, placed behind the chamber, used for the event trigger. Additionally, we will measure the phototube signals from the scintillator array with ADC's to provide particle identification. For Phase 0, we used a smaller, 5-bar array in conjunction with S1 to provide a simple event trigger.

Phase 0 Preparation (Spring, 1992)

Phase 0, the testing and development phase of the experiment, consisted of four major goals. First, we tested the overall performance and stability of the chamber, specifically its ability to hold high voltage over an extended period of time without breakdown, which had proven troublesome during 1991. Second, we measured the horizontal and vertical chamber resolutions, to see if they satisfied the proposed resolutions needed for Phases 1 and 2. Third, we determined the wire hit efficiency of the chamber, and attempted to maximize this value. The value of the efficiency is not only crucial to obtaining good data, but must be known precisely in order to extract a differential cross

section. Finally, we tested the overall tracking ability of the chamber directly with cosmic and beam particle data, and continued in the process of extrapolating the total chamber efficiency and resolution further through Monte Carlo analysis.

Figure 2: Phase 0 Parasitic Operation

To accomplish these goals, we ran the chamber in parasitic mode, behind the existing E876 apparatus (see Figure 2), where a horizontal flux of recoil protons from the E876 LH2 target could pass through the chamber. Eleven modules of sense wires (16 wires each) were added to the eight from the previous year, so that the entire downstream half of the chamber and four upstream modules could be used. The upstream modules, centered between the Phase 2 target insert holes in the chamber walls, allowed the tracking of particles through the entire chamber, as well as testing with a Sr beta source (which cannot penetrate the walls). For the majority of the summer, the number of FERA units (see below) available limited us to 10 chamber modules, which we called the "Base 10" configuration and arranged in a way to provide tracking of recoil protons entering and leaving the chamber as well as scattered protons from a block of CH_2 placed in the target area. Additionally, thin horizontal scintillators, placed before and after the chamber and vertically adjustable, provided for testing of the chamber performance along the length of the wires.

The major task needing completion prior to Phase 0 operation involved the replacement of the existing wire chamber electronics, which had proven unsatisfactory in previous runs, with that of the LAMPF MEGA collaboration. These electronics consist of

preamps (PA) mounted on the chamber, which are connected to a module of 16 sense wires with short leads (see Figure 3). A preamp mount (PM) holds the PA close to the appropriate module, minimizing the length of the sense wire leads, and provides it with power. The PA amplifies the chamber pulses, and sends these signals along a 15 ft. coaxial flat cable to the shaping amps (SA), housed in powered crates. Here, the SA broadens the pulses and sends the passive addition of top and bottom sense wire signals to the discriminator board (DB), which forms the TDC stop signal. These functions take place in the experimental area, and the two ADC pulses and TDC stop signal from each wire are carried to the counting house by 250 ft twisted pair flat cable.

Figure 3: Wire Chamber Electronics

We perform the ADC and TDC operations with the LeCroy FERA (Fast Encoding and Readout ADC) system. Each sense wire module uses two 16-channel FERA for the top and bottom ADC's and a TFC (Time to FERA Converter) / FERA combination for the TDC. The TFC feeds the FERA an amount of charge, in the form of a square pulse, linearly proportional to the arrival time of the DB stop signal. A FERA DRV (Driver) provides the FERA modules with gate information, and transfers the ADC output to a memory module (MEM), read by the computer between beam bunches. A single CAMAC high powered crate holds the DRV, MEM, and 18 FERA, bypassing the problem of branching FERA crates found previously.

To link the MEGA electronics with our FERA system, we found that a receiver board (RB) is needed, which performs 3 basic functions. First, the RB reverses the polarity of the SA output signals before input to the FERA. Next, a capacitor between the FERA signal and ground inputs stops the injected pedestal charge from bleeding to ground. Lastly, a transformer decouples the FERA from the 250' flat cable, to prevent an observed smearing of the pedestal. These necessities had been discovered independently by the LAMPF NMS group, which uses the same flat cable and FERA system and had manufactured 16-channel RB's for that purpose. We were able to borrow some of these boards in time for Phase 0 operation.

Therefore, we were able to integrate the MEGA electronics into our existing system without direct modification of the MEGA boards. In so doing, we also discovered a major source of electronics noise in the chamber high voltage system, which produced an oscillation on the sense wires detectable as a significant broadening of the ADC pedestal. By simply adding a 1 Megaohm resistor in series with the HV wires, we eliminated this ripple, improving our charge resolution by a factor of ten. The charge resolution of a single wire, derived from the ADC pedestal width, was then found to be less than 1%.

Phase 0 Results (Summer, 1992)

In June and July, we ran the detector with both cosmic and beam particles to accomplish the Phase 0 goals. Testing the overall chamber stability, our first goal, we maintained the "Base 10" modules, over a third of the chamber, for the duration of the summer. We learned to diagnose and fix chamber voltage problems quickly and efficiently. These problems usually involved the breakdown of the plastic inserts holding the HV wires at either end, which we solved easily by simply replacing the wire.

To determine the vertical and horizontal resolutions of the chamber, we invented a series of calibrations performed on each wire individually, since every wire's electronics have slightly different properties (amplifier gain, wire resistance, discriminator level, etc.). For the horizontal component (see Figure 4), measured via drift time, we define not a drift distance but a drift angle, due to the cylindrical geometry of the chamber (which causes wire cells on separate layers to have slightly different size). This value defines the angle between the sense wire and the intersection of the particle track with the sense wire cylindrical plane, so that, dividing by the total wire cell angle, we define a drift angle ratio ranging from 0 to 1 that is the same for all wires. We can calibrate each wire individually if we assume that the distribution of drift ratios (and therefore the flux of particles) is uniform over the sense wire cell. We then integrate the TDC values to fill a uniform distribution. To test this calibration, we define a drift residual using the cylindrical angle of the particle track. For a layer pair of hits, the sum of the two drift ratios, plus the track dependent angle ($\Delta\Phi$), should equal the total angle between the sense wires. Dividing by twice the cell angle, and subtracting 1,

we arrive at a residual peaked at 0, with a spread proportional to the drift resolution. Using such a method (see Figure 5), we found a resolution near 10% of the total drift cell (or about 1mm in distance), satisfying the original proposal's requirements but still in need of refinement. Figure 5 also shows an example event, with the circles showing the hit wire positions, and the crosses denoting the hits with added drift angles, which align well to reveal a single track through the center of the chamber.

Figure 4: Horizontal (Drift) position Geometry

The vertical component (Z-position) for track hits is determined through charge division of the top and bottom ADC signals from a given wire, which we can derive rather simply assuming that the resistive wire and associated electronics behave as a DC circuit:

$$Z = Z_0 \frac{Q_t - Q_b}{Q_t + Q_b} \rightarrow Z_0 = \frac{L}{2} + \frac{R_p}{\lambda}$$

Figure 5: Drift Calibration and Resolution

Here, Q_t and Q_b are the top and bottom charges, and the parameter Z_0 is a function of the wire length (L), the preamp resistance (R_p), and the wire resistance per length (λ). The resolution (ΔZ) is parabolic in Z -position (with a minimum at $Z = 0$) and linear in the charge resolution, or ratio of charge error to total charge, ($\Delta Q/Q$):

$$\Delta Z = \sqrt{2(Z_0^2 + Z^2)} \frac{\Delta Q}{Q}.$$

Using this formula for Z , a first order calibration, which measures and subtracts the individual ADC pedestal values from each wire, correctly aligns the Z -position spectra for the wires over the entire range of the chamber, and produces a resolution under 2% (see Figure 6). We calculate this Z -resolution by plotting the residual deviations of individual wire hit values from the track Z -positions. A look at the ADC spectra shows why the resolution cannot improve further; the ADC pedestal width, while clearly separated from the hit spectra, produces a charge resolution greater than 1%. Since the single-wire charge resolution is less than 1% (as stated above), this pedestal broadening clearly reveals the effect of crosstalk between the wires, which we must remove in order to achieve the desired resolution.

Figure 6: First Order Vertical (Z-position) Calibration

Inspection of this crosstalk shows that it actually occurs from two independent processes. The first source, a true crosstalk between wires within a module (since these channels share a common ground throughout the electronics), results in a positive shift of pedestal values if a given wire within the module receives a large negative pulse. This effect, however, is not consistent enough to be removed. The second source of the pedestal broadening, we believe, results from a feedback between the top and bottom amplifiers of the electronics through the sense wires, which we can observe with an oscilloscope as approximately a 50 MHz ripple, and produces an oscillation in the pedestal value of the ADC's. A strong correlation in this oscillation exists between the top amplifiers, which are in turn anti-correlated with the bottom amps. Because of this correlation, we can determine the phase of the oscillation for a given event, and subtract it from the ADC values, to reduce the overall charge resolution to the desired 1%.

We perform a final calibration to take care of asymmetries between the top and bottom electronics of an individual wire. If we assume that this asymmetry results from differences in the preamp input impedances (which may be as large as 10%), then the charge division equation becomes:

$$Z = \frac{Z_t Q_t - Z_b Q_b}{Q_t + Q_b} \rightarrow Z_t = \frac{L}{2} + \frac{R_t}{\lambda}, \text{ etc.}$$

where Z_t and Z_b are the top and bottom preamp resistances. Using an iterative procedure, the Z parameters of a wire are adjusted relative to each other to bring the wire's hits in line with groups of other hits from the same track. When all calibrations are performed, the Z -resolution can be reduced to under 1% to achieve the proposal's requirement (Figure 7).

Figure 7: Higher Order Z-position Calibrations

Investigation of the chamber efficiency, our third Phase 0 goal, showed two factors of importance. The first factor results from the proximity of the wires to the chamber carbon walls, which are held at ground and therefore alter the HV field, lowering the wire efficiency as expected. Fortunately, this effect occurs only for the inner and outer sense wire planes, and can be compensated for, somewhat, by raising the HV level in these planes. In general, the inner planes have efficiencies around 97–99%, while the outer planes range from 80–90%. Second, the Z-position of the hits along the wire also affects the efficiency; since the top and bottom chamber plates are, like the walls, held at ground, the HV field and therefore the efficiency should deteriorate towards the chamber ends. However, we found the average efficiency fairly uniform along the wire, up to about 8 cm from the chamber endplates.

The final goal of the Phase 0 runs was to test the tracking ability of the chamber. The majority of events recorded came from single recoil protons or cosmic particles traversing the entire chamber. The tracking software, working on or off-line, proved successful in reconstructing these events (see Figure 8). For a few runs, when the beam intensity was high, we observed elastic scattering events from a CH₂ target placed in the chamber center, distinguishable by a 90° separation of the final state particles (Figure 9). We also recorded a candidate inelastic event (3-particle final state), but these scattering events were rare due to the limited acceptance region of the “Base-10” modules.

Figure 8: Beam and Cosmic Particle Events

Figure 9: Elastic and Inelastic Scattering Events

We presented these results to the LAMPF PAC on August 19, 1992, which recommended 500 hours of 800-MeV beam for 1993 with A⁻ priority. The committee, concentrating on the progress and prospects for Phase 1, expressed the opinion that a 10–20% measurement of the differential cross section would “contribute significantly to the understanding of the $I = 0$ NN interaction and of pion production processes”. The PAC also stressed the need for more manpower to achieve this goal.

Phase 1 Preparation (Fall, 1992)

Several projects were undertaken in preparation for Phase 1 operation in 1993. Of primary importance, due to budgetary constraints, was the implementation of multiplexing, which reduces the number of FERA and 250' flat cable needed, two of the major costs associated with the chamber, by sharing these items between modules. We perform this multiplexing most easily by making a passive flat cable connection between modules after the SA, since we do not need to save on MEGA electronics. If each sense wire retains its own TDC stop signal (and hence its identity), we can then multiplex groups of wires in which only one hit is predicted. This situation occurs in the pion region of phasespace, beyond a scattering angle of about 60° (totaling $2/3$ of the chamber). The obvious effects of this multiplexing are a reduction in the signal size and an adding of the signal noise, which hurts the resolution. The multiplexed modules can be run at a higher voltage to minimize the signal loss, so that the total loss of resolution is only about 0.2%.

Another factor affecting the budgetary limitations concerned the redesign of the scintillator array. This revision uses existing scintillator bars and phototubes similar to those used in Phase 0 to create a 21-bar array. We sacrificed the ability to measure particle flight times (proposed originally) and relied instead on particle identification through analysis of the phototube signal charge, measured with FERA ADC's. We can therefore move the scintillator bars closer to the chamber to increase their acceptance.

Next, we finalized the designs for the double level trigger system electronics (see Figure 11). The first level, formed by the scintillator array, signals the start of the event, and sets the gates for the FERA electronics. This trigger involves a coincidence between S1 and a programmable multiplicity of bar hits in the scintillator array (probably $N \geq 2$) combined with a rudimentary pattern logic within the array. This pattern design satisfies conservation of momentum while minimizing the occurrence of triggering on neutron conversion in the bars (which can fire neighboring scintillators). Since certain background events (for instance, $nn \rightarrow np\pi^-$) can mimic a 2-bar trigger, a second level trigger uses multiplicity units to count the number of chamber wire hits in order to determine 3-track events (which can only occur for $np \rightarrow pp\pi^-$). Failure to satisfy this condition stops the event and resets the electronics within a few μsec , which reduces the dead-time involved in reading out the FERA data.

Figure 10: Phase 1 Scintillator and Chamber Stands

Finally, to determine the detector resolution and efficiency as a function of phasespace, we began to input the single-wire values found above to a Monte Carlo simulation linked to the current tracking and reconstruction software. These calculations were to be used to derive the differential cross section, a major motivation for Phase 1, as emphasized by the PAC report.

Figure 11: First and Second Level Triggers

For this purpose, we implemented the CERN library code GEANT, which generates particle 4-momenta for events, including the physical processes of energy loss, multiple scattering, and particle decays. The existing tracking program then converts the simulated 4-momenta to detector hits, incorporating the efficiencies and resolutions measured in Phase 0. Lastly, we can perform the tracking and event reconstruction on the simulated hits to deduce the tracking efficiency and resolution as a function of phasespace. Figure 12 shows a typical $np \rightarrow pp\pi^-$ event, generated by GEANT and propagated through the detector apparatus, where the pion has decayed prior to entering the chamber.

Figure 12: Monte Carlo Simulation Event

D. BNL E871, A New Search for Rare Kaon Decays

Overview

The kaon system is one of the best laboratories for the study of conservation laws in particle physics and in particular for the search for processes forbidden in the Standard Model. The experimental absence of processes which violate separate lepton number (i.e., electron, muon, or tau lepton number), also called lepton flavor or lepton family number, has led to its conservation being formalized in the Standard Model. The underlying basis for such a conservation law remains mysterious. In a gauge theory, a globally conserved quantity is associated with the existence of a massless boson. In the case of charge conservation, the associated boson is the photon. Separate lepton number conservation has no associated massless boson and is therefore, according to current theoretical thinking, unlikely to be exact. It is more likely that lepton flavor transitions are highly suppressed in some dynamical process which lies outside the Standard Model. This is the general motivation for searches for separate lepton number violating processes, such as $\mu \rightarrow e\gamma$, $\mu \rightarrow eee$, $\mu^- A \rightarrow e^- A$, (muon-electron conversion in the field of a nucleus), and in the kaon system, the decays $K_L \rightarrow \mu e$ and $K^+ \rightarrow \pi^+ \mu e$.

Even as the Standard Model continues to pass every test, the theory is generally considered to be incomplete. The reasons for this view can be traced to several problems: (1) there are nineteen free parameters in the theory, (2) there is no explanation of why the quarks and leptons appear in three generations, or why there should not be more, (3) there is no explanation of how the quarks and leptons are related, (4) there is a technical difficulty known as the "gauge hierarchy problem," which refers to the need for unnatural fine-tuning of parameters, (5) there is no unification of the strong and electroweak interactions (and gravity is not in the picture at all). Attempts to repair these difficulties have led to a number of proposed extensions to the Standard Model, including supersymmetry[1], technicolor[2], right-left symmetry[3], horizontal gauge symmetry[4,5], compositeness[6], and some superstring inspired models[7]. Typically, lepton flavor violation occurs in these extensions. The process $K_L \rightarrow \mu e$ is one of the most sensitive probes for lepton flavor violation.

$K_L \rightarrow \mu e$

The decay $K_L \rightarrow \mu e$ or other separate lepton number violating processes, can occur in the Standard Model if the neutrino masses are not zero or degenerate. In a gauge theory such as the Weinberg-Salam electroweak model, the eigenstates of the weak interaction need not be mass eigenstates. As discussed earlier, the quark weak eigenstates differ from the mass eigenstates and are connected through the unitary CKM mixing matrix. The same sort of mixing among the leptons would be expected[8] were it not for the fact that the neutrinos are massless or very nearly so. However, existing limits on neutrino masses and couplings imply[9] $B(K_L \rightarrow \mu e) < 10^{-25}$, which is unobservable.

Consequently, observation of $K_L \rightarrow \mu e$ depends on new physics outside the Standard Model.

In considering a search for lepton flavor violation in $K_L \rightarrow \mu e$, it is reasonable to ask to what extent other measurements probe the same possible new interactions. Related processes include: (1) $\mu \rightarrow e \gamma$, (2) $\mu \rightarrow e e e$, (3) $\mu A \rightarrow e A$ (muon conversion on a nucleus), (4) Δm_K (the K_L - K_S mass difference) and (5) the decay $K^+ \rightarrow \pi^+ \mu e$. Processes such as $\mu \rightarrow e \gamma$ and $\mu \rightarrow e e e$ only involve leptons (no quarks) in the initial or final state, so that any interaction depending upon the participation of quarks (e.g., generation number conserving interactions, composite models) are not probed at all. While the process $\mu A \rightarrow e A$ is a very powerful probe in many models, it also does not involve a generation-change in the quark sector, so that an important class of interactions is not tested. The small value of Δm_K (3.5×10^{-15} GeV) is a serious constraint in a broad range of models. However, a sensitivity of 10^{-12} for $K_L \rightarrow \mu e$ is beginning to be competitive with Δm_K , as discussed below. Also, leptoquark exchange, since it cannot induce a $K^0 - \bar{K}^0$ transition, is not constrained at all by Δm_K . Finally, the decay $K^+ \rightarrow \pi^+ \mu e$, while suffering from smaller phase space than $K_L \rightarrow \mu e$ and the shorter K^+ lifetime, is ultimately complimentary to $K_L \rightarrow \mu e$ rather than competitive with it, since the former probes a scalar or vector interaction and the latter a pseudoscalar or axial-vector interaction.

Table 1: Mass reach of separate lepton number violating processes in the Cahn and Harari model. The β 's are generation mixing angles and are unconstrained.

Process and Present Value	Mass Reach
Δm_K (3.5×10^{-15} GeV)	400 TeV $\sin \beta_D$
$\text{Br}(\mu \rightarrow e \gamma) < 1.7 \times 10^{-11}$ [10]	20 TeV $ \sin \beta_L \cos \beta_L ^{1/2}$
$\text{Br}(\mu \rightarrow e e e) < 1 \times 10^{-12}$ [11]	80 TeV $ \sin \beta_L \cos \beta_L ^{1/2}$
$\Gamma(\mu A \rightarrow e A) / \Gamma(\mu A \rightarrow \nu A) < 4.6 \times 10^{-12}$ [12]	190 TeV $ \sin \beta_{LU} - \sin \beta_{LU} ^{1/2}$
$\text{Br}(K^+ \rightarrow \pi^+ e^- \mu^+) < 2.1 \times 10^{-10}$ [13]	40 TeV
$\text{Br}(K_L \rightarrow \mu e) < 8.4 \times 10^{-11}$ [14]	70 TeV
$\text{Br}(K_L \rightarrow \mu e) < 2.0 \times 10^{-12}$ (E871 planned)	180 TeV

In order to make this discussion more quantitative, we will use the often cited model of Cahn and Harari[5] for generation-changing gauge bosons to illustrate the relative power and present status of limits from the various lepton flavor violating processes. Table 1 lists the best present limit for each process and the mass scale probed by that limit in the Cahn and Harari model. The bottom row shows the mass reach of the new experiment (E871).

$K_L \rightarrow \mu\mu$

The decay $K_L \rightarrow \mu\mu$ played a major role in the development of the Standard Model, as its small value led to the GIM mechanism which invoked the existence of a fourth quark, charm. The decay rate is dominated by the 2-photon intermediate state, as seen from the fact that the branching ratio is consistent with the absorptive (imaginary) amplitude ($K_L \rightarrow \gamma\gamma \rightarrow \mu\mu$) alone, a value usually referred to as the unitarity bound. The standard value of the unitarity bound[15] is given by:

$$\Gamma(K_L \rightarrow \mu\mu)_{abs} = 1.2 \times 10^{-5} \Gamma(K_L \rightarrow \gamma\gamma).$$

The Particle Data Group[16] lists $(5.70 \pm 0.27) \times 10^{-4}$ as the branching ratio for $K_L \rightarrow \gamma\gamma$. Therefore, the unitarity bound is about 6.8×10^{-9} . (There is a theoretical uncertainty at the 10 to 20% level, on top of the experimental uncertainty of $Br(K_L \rightarrow \gamma\gamma)$, so this is not a rigid bound.) Recent measurements of $K_L \rightarrow \mu\mu$, which are dominated by E791, are close to this value, so that the dispersive amplitude is evidently small.

Interpretation of the $K_L \rightarrow \mu\mu$ branching ratio is made difficult by the long-distance nature of the dominant 2- γ contribution. Short-distance contributions to $K_L \rightarrow \mu\mu$ have been evaluated[17] and the general consequence of a small dispersive amplitude for $K_L \rightarrow \mu\mu$ is to limit the magnitude of the real part of the CKM product $V_{ts}^* V_{td}$ as a function of the top mass. Some recent theoretical analyses[18] use the recent results from BNL and CERN on the $K_L \rightarrow e e \gamma$ form factor in estimating the long distance part of the $K_L \rightarrow \mu\mu$ dispersive amplitude. They then derive constraints on the short distance part, using the $K_L \rightarrow \mu\mu$ branching ratio, which in turn constrains CKM parameters. One conclusion of this analysis is that the branching ratio for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ is probably smaller than previously expected.

 $K_L \rightarrow ee$

The decay $K_L \rightarrow ee$ also receives a contribution from the 2- γ process that dominates $K_L \rightarrow \mu\mu$. However, this contribution is helicity suppressed, so that the expected branching ratio is much smaller than $K_L \rightarrow \mu\mu$. The suppression, however, is not simply a factor of (m_e^2/m_μ^2) , which would reduce it to the 2×10^{-13} level. Instead, there is a logarithmic singularity as $m_l \rightarrow 0$ in the total electrodynamic cross section for $\gamma\gamma \rightarrow l^+ l^-$ which modifies the naive factor by more than an order of magnitude. Consequently, it is expected[15] that $K_L \rightarrow ee$ occurs at a branching ratio of about 3×10^{-12} . The range between this value and the $K_L \rightarrow \mu\mu$ level is a window for observing a new flavor changing neutral current interaction, such as the pseudoscalar leptoquarks that appear in extended technicolor theories[19]. Of course, part of this window has already been closed, as discussed in the next section.

Results of E791

Three experiments have been active over the last few years in the search for the rare modes $K_L \rightarrow \mu e$, $K_L \rightarrow \mu\mu$, and $K_L \rightarrow ee$. They were BNL E780, KEK E137 (in Japan), and BNL E791.

AGS Experiment 791 took data in three consecutive years of running—1988, 1989 and 1990. No $K_L \rightarrow \mu e$ or $K_L \rightarrow ee$ candidates were found. Final results have not been published yet, but preliminary values of final results are given in Table 2. The table also includes, for comparison, the final results from both AGS E780 and KEK E137. As is clear from the table, E791 has dominated this research. The new experiment, E871, to be carried out by substantially the same collaboration, will improve upon E791 by more than an order of magnitude.

Table 2: Results from recent $K_L \rightarrow \mu e$ searches.

	BNL780[20]	KEK137[21]	BNL791
$K_L \rightarrow \mu e$ limit	1.9×10^{-9}	9.4×10^{-11}	3.3×10^{-11}
$K_L \rightarrow ee$ limit	1.2×10^{-9}	1.6×10^{-10}	4.1×10^{-11}
$K_L \rightarrow \mu\mu$ sample	~8 events	178 ± 13 events	717 ± 27 events

Overview of The New Experiment, E871

E871 will improve upon E791 by more than an order of magnitude in sensitivity. We have re-used a significant part of the existing E791 detector, thereby moderating the cost and time scale. The major data-taking will be during the 1994 and 1995 SEB periods. We expect to be able to set a limit on $K_L \rightarrow \mu e$ at or below 2×10^{-12} , if no signal is observed. At this sensitivity, we would observe a few $K_L \rightarrow ee$ events.

Our approach to the new experiment depends on detector modifications which will provide significantly increased acceptance and the ability to run with a factor of about four more beam (over E791). In addition, improvements to several parts of the experiment will decrease losses due to inefficiencies and deadtimes. The key features of the new experiment are:

- The decay volume has been lengthened from 8meters to 11meters and detector apertures increased by using the existing 96D40 magnet as the upstream spectrometer magnet and a 100D40 magnet, obtained from Fermilab, as the second dipole. These changes account for more than a factor of two improvement in acceptance.

Figure 1: Plan view of the E871 detector apparatus.

- A beam stop, or plug, has been inserted in the 96D40 to stop the neutral beam. Extensive beam tests carried out during the 1991 AGS SEB running demonstrated that our beam plug design is viable. The plug will reduce rates in detector elements

downstream of the 96D40, by eliminating K_L decays inside the spectrometer, beam scraping on detector frames, neutron interactions in the gas, etc. The net effect will be clearer particle identification. Also, the enormous reduction in dose to the lead glass (to levels well below E791, even at the increased Booster intensity) will make it possible to re-use that system.

- The two dipoles are operated with opposite fields, but tuned to provide a net p_T -kick of about 220 MeV, which makes daughters from 2-body K_L decays approximately parallel to the beam direction. (This parallelism will be used in forming the Level 1 trigger.) The events that will be accepted are the so-called "in-bends", in which both charged particles bend toward the beam in the upstream dipole. The "out-bends", which first bend away from the beam, will not be accepted in this magnet configuration.
- New tracking chambers are being built. The four upstream-most tracking stations will be straws with wire spacing approximately 1/2 of E791 (i.e., 0.5cm diameter cells). We will have three, rather than two, planes of x measuring wires in each chamber; E791 experience shows that this added redundancy in the bend plane of the magnets will provide improved background rejection. The smaller cell size will reduce the occupancy of each channel by a factor of four. An additional reduction of approximately a factor of two will be obtained by using a faster gas than in E791.
- The fifth and sixth chambers, those downstream of both magnets, are sufficiently distant from the plug that rate is not a problem. For these chambers, a 1cm pitch should be acceptable and conventional drift chambers following closely the E791 design have been built.
- A new Cerenkov counter, with improved optical properties, has been built.
- The E791 lead glass array has been reused, but reconfigured and substantially upgraded.
- A new muon trigger hodoscope has been built. New trigger scintillators provide a muon momentum threshold of 1.0 GeV/c (rather than 1.6 GeV/c in E791), thereby increasing acceptance by about 10%, as well as incorporating parallelism into the muon signal. The existing E791 muon hodoscope counters have been re-used in four planes of the detector and placed throughout the muon rangefinder to improve timing resolution for muons.
- The muon rangefinder has been reconfigured to increase the momentum range it covers and improve the resolution of the range measurement by approximately a factor of two over E791.

- The Level3 trigger has been upgraded by replacing the farm of eight SLAC 3081/E processors with eight (or more if appropriate) modern RISC processors, resulting in an approximate order of magnitude increase in on-line computing power.

The result of these changes will be an experiment with larger acceptance and a capability to run with much higher beam intensity with improved background rejection compared to E791. The layout of the new experiment is shown in Figure 1.

We have adopted a method of estimating E871 sensitivity that we believe is both realistic and reliable. We have scaled from a well-understood data set in E791. Details of this estimate can be found in the E871 proposal and are not reproduced here. Since the modes $K_L \rightarrow \mu e$, $K_L \rightarrow ee$, and $K_L \rightarrow \mu\mu$ have different acceptances and are affected differently by changes in particle identification efficiencies, they are listed separately in the Table 3. The 1989 E791 sensitivities for observing a single event of the types $K_L \rightarrow \mu e$ and $K_L \rightarrow ee$, and the actual number of $K_L \rightarrow \mu\mu$ events observed, are given. The table also shows the full improvement factor for each mode and the expected sensitivities for the proposed experiment.

Table 3: Sensitivity of the new experiment.

	E791 1989 Data	Improvement	E871
$K_L \rightarrow \mu e$ sensitivity (single event)	3.6×10^{-11}	43	8.4×10^{-13}
$K_L \rightarrow ee$ sensitivity (single event)	4.8×10^{-11}	56	8.5×10^{-13}
$K_L \rightarrow \mu\mu$ observed	284 events	34.5	9800 events

Lead Glass Detector for E871

The principle function of the lead glass is electron identification. The E871 lead glass detector consists of two large arrays of lead glass blocks. The converter array, consisting of 36 blocks covers a horizontal width of 72 inches and a vertical height of 71 inches, while the downstream array of back blocks covers a horizontal width of 84 inches and a vertical height of 72 inches, both arrays centered on the beam centerline. The array has been sized to account for electromagnetic shower spreading. The layout for the array is shown in Figure 2.

E791 Experience and Improvements

The experience of building and maintaining the E791 lead glass system, as well as calibrating it and using it for particle identification, has provided several lessons on how to do things better. The single largest improvement was to eliminate photomultiplier tubes (PMT's) whose performance has proved marginal in E791. All

36 converter PMT's have been replaced along with 50 back block PMT's. Other improvements include building new PMT bases (E791 bases were recycled from previous experiments). The new bases will provide more reliable performance and will be designed with an additional amplified output (approximate gain of 30) to provide signals for muons in the glass. This will provide a considerably enhanced ability to calibrate the system (muons were effectively inaccessible in E791 for calibration purposes). While we do not expect significant radiation damage in E871, the option of UV curing between E871 runs has been maintained in the construction of the light-tight, temperature-controlled enclosure which houses the array. The roof of the housing allows for removal of the converter blocks, permitting access to the back block array. We have also been making improvements to the laser-based flasher system. The combined effect of these changes is to improve the function and make maintenance of this system significantly easier.

Figure 3 shows the ratio of electromagnetic shower energy as measured by the lead glass to track momentum as measured by the magnetic spectrometer for Cerenkov tagged electrons for two regions of the E791 lead glass array. One region has several of the E791 marginal PMT's, which are now replaced, while the other region has mostly good PMT's. The potential improvement from the PMT upgrade is obviously

Results from the 1993 Engineering Run

The major endeavor of the engineering run for the lead glass detector was to test the prototype PMT bases. These bases have, in addition to the nominal output, an amplified output for the purpose of observing muon induced signals in the lead glass. The 8-bit ADC precision makes observation of muon signals in the unamplified signal difficult, due to the limited precision at the low-end of the ADC dynamic range where muons appear. The amplified signals will provide an additional means of establishing and monitoring the lead glass calibration and may ultimately be used to identify muons in the rare decay analysis.

Figure 2: E871 Lead Glass Detector

Figure 3: E/p for electrons in the E791 lead glass for two regions; the left plot shows the performance of marginal PMTs, which will be replaced in E871.

During the 1993 engineering run the prototype PMT bases were connected to a 25 block square on the back array plus several upstream converter blocks. The bases were cabled as they will be in future data runs, running both the amplified signal and the nominal output to the ADC's. Figure 4(a) shows a typical ADC pulse height distribution for the amplified signal from a lead glass block, in units of pico-Coulombs. Figure 4(b) shows the distribution in the same block for events selected by requiring an associated converter block (i.e., a block located upstream and immediately in front of the block of interest) to have pulse height consistent with a muon. Figure 4(c) shows the ratio of the amplified signals to the unamplified signals for a typical test base. The width of the distribution is mainly a result of the coarse binning of the unamplified signal at the low end of the ADC dynamic range.

Figure 4: a) ADC spectrum for amplified signal; b) spectrum with converter block coincidence; c) ratio of amplified and unamplified signals.

Muon Hodoscope

Design and Construction

The purpose of the Muon Hodoscope (MHO), also known as the Instrumented Muon Filter (IMF), is twofold: (1) to produce a trigger for parallel muons to the Level 1 trigger logic, and (2) to measure the muon momentum in the range of 1.0 to 5.8 GeV/c. Factors affecting the overall design of the MHO were the desire to reuse existing scintillators and phototubes from E791 for cost savings and the need to minimize air gaps within the detector to reduce loss of acceptance from multiple scattering and straggling (definition?).

Figure 5: E871 Muon Hodoscope.

Using these criteria, the construction of the MHO was begun at Texas in January of 1993, with final installation at Brookhaven completed by June, in time for a July

engineering run (see Figure 5). The hodoscope consists of 6 planes of scintillators ($X0,1,2$ and $Y0,1,2$) separated by 16 stacks of the original marble slabs used in E791, as well as 26 new iron plates at the upstream end, which reduce acceptance loss as compared with the marble. Interspersed, and extending beyond, the MHO are 49 Muon Range Finder (MRG) gas counters distributed at intervals of 5% in muon momentum. The combined MHO and MRG detectors can make range measurements for muons with momenta between 1.0 and 9.7 GeV/c.

Figure 6: MHO plane schematic.

The planes $X0$ and $Y0$ are used for the trigger signal, as well as range measurements, and so contain new Bicron scintillators to spacially match the trigger counters upstream, in order to form a parallel trigger. Thus the planes are symmetrically divided along the beam axis, with $X0$ containing 18 vertical bars with Philips XP2262 phototubes (and 5628OJ bases) on both ends, and $Y0$ having 18 single-ended bars, with 9 bars on each

side (see Figure 6). These planes sit at a depth corresponding to the range of a 1.0 GeV/c muon. The parallelism requirement itself must not be too tight, due to the multiple scattering dominated by the PbG array directly upstream, which produces a root-mean-square spread of about 12 cm for 1.0 GeV/c muons at these trigger counters.

The four MHO planes X1, Y1, X2, and Y2 consist of scintillator bars and phototubes reused from E791, housed in newly constructed frames, and placed at muon ranges corresponding to 0.75, 1.5, 2.8, and 5.8 GeV/c. X1 and X2 contain 11 vertical double-ended scintillator bars, while Y1 and Y2 have 14 horizontal bars with a single tube. All MHO scintillator phototube outputs go to LeCroy 4413 Discriminators, and then to Stanford Fast TDC's for timing information with 1 ns resolution, making up for the lack of timing from the MRG counters, whose outputs are merely latched over a 150 ns time window. Additionally, outputs from X1 tubes are split before the discriminator, with a signal going to ADC's for an independent energy verification. The overall energy determination in the 1.0 to 2.8 GeV/c region due to the MHO is 5%.

Results of Engineering Run

The overall performance of the MHO was tested during the July run via analysis of the TDC and ADC data, as well as the triggering mechanism. By simply defining a single phototube efficiency for the X-bars by comparing hits in a tube with those at the other end of the bar, the tube efficiency was found to range from 96-98%. For a particular 5.8 GeV/c trigger run (described below), we have:

Plane	Efficiency (%)	Plane	Efficiency (%)
X0TL	96.9	X1T	95.9
X0TR	95.4	X1B	96.1
X0BL	96.8	X2T	97.9
X0BR	96.2	X2B	96.6

In Figure 7, a rudimentary track efficiency is also calculated by comparing the number of tracks in a plane (simply the number of non-adjacent bars hit) with the number in the next downstream plane (for Y2, this comparison is made with X2, and so is more a function of momentum distribution of the muons).

Figure 7: MHO track efficiency.

In addition to the 1.0 GeV/c muon trigger from X0 and Y0, a 5.8 GeV/c trigger was constructed with X2 and Y2 to aid in studying these lower rate downstream detectors. In Figure D, abstract top and side views of the MHO planes relative to the TSC counters show such an event, with the left (lower) track forming the 5.8 GeV/c trigger, and the right (upper) track extending to a range beyond Y1 (1.5 GeV/c).

To maintain the thermal stability of the MHO phototubes within the scintillator bar frames, electric exhaust fans were installed on each tube encasement section. The temperature was then monitored with a thermistor system using a scanning ADC to measure changes in thermistor resistance (and therefore temperature), showing the cooling system will indeed prevent tube overheating.

BNL Experiment 888

In a collaboration between the E871 group and physicists from Princeton, UCLA, and BNL, a search for an H dibaryon has been conducted at the AGS, using the E791 spectrometer, with approximately 10 days of data taken in June, 1992. Currently, no experimental verification of six quark states exists. However, according to Jaffe[22], the most likely possibility for such a dibaryon state to be found is the H particle, a spin and isospin singlet state of $uuddss$, which is more stable than other six quark configurations due to the stronger binding between unlike quark pairs.

The experimental strategy of the H search is twofold, the first being the detection of Λ 's produced in the reactions:

$$\begin{aligned} H &\rightarrow \Lambda n \\ H &\rightarrow \Sigma^0 n, \Sigma^0 \rightarrow \Lambda \gamma \end{aligned}$$

by reconstructing these secondary Λ 's from their two-track decay $\Lambda \rightarrow p\pi^-$. Since the z -position of the reconstructed vertex depends on the decay lifetime of the H , any vertices significantly different from those of primary Λ 's should signify the production of an H particle. Since this search is similar to that of the two-body $K_L \rightarrow \mu e$ search, the entire E791 apparatus was able to be used with only slight modification, and sensitive to H lifetimes in the range 10^{-7} to 10^{-9} . One adjustment was to the trigger, since the Λ decays hadronically instead of the dileptonic decay of the K_L . Also, the Cerenkov counter was filled with freon in the beam-left portion of the chamber for approximately half of the data collection to aid in the suppression of background from K_L decays.

The second strategy in the H search involves a dissociation experiment, where two Λ 's are produced in the diffractive dissociation:

$$H + A \rightarrow H^* + A \rightarrow \Lambda\Lambda + A$$

Here, H^* is an excited state H particle, with a large enough mass to decay into two Λ 's via the strong interaction, and A is a target nucleus in the active (scintillator) dissociator. The mass of the H can be reconstructed from the decay products of the $\Lambda\Lambda$ diffracted state, and the experiment is sensitive to H lifetimes of the order 10^{-8} . However, since the high momentum protons from these decays tend to follow trajectories close to the beam line, the original E791 layout, with gaps between the left and right spectrometer arms, was unacceptable. To correct for this problem, the first spectrometer magnet (with active dissociator inside) went unused, and the left and right sides of the third drift chamber were aligned along the beam axis. Since the second magnet bends the protons in the opposite direction of the pions, as well as at a much smaller angle, the drift chambers downstream of the second magnet were moved off

line from the beam axis, as well as further away, to improve acceptance and tracking ability.

Analysis of the two-body decay H search is under way, aided by the similarity with the K_L decay, making the existing E791 offline software suitable, with few corrections. Currently, all data runs have been analyzed to the first pass level, including pattern recognition, track fitting, and event selection using a loose cut on lambda mass. Additionally, efficiency and resolution measurements of the detectors have been made using both magnet-on and magnet-off runs, as well as corrections to the magnetic field itself. Analysis of the dissociation experiment has been complicated by the differing apparatus, and hence the need for new offline software code, as well as full surveying and calibration of the detectors.

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E. STAR - Solenoidal Detector at RHIC

Recently, we have joined a large collaborative group working on the RHIC experiment STAR (Solenoidal Detector at RHIC) at BNL. Our role in this project, which for the next several years will emphasize the design and fabrication of a very large, complex collider detector, is not yet fully defined, but will clearly involve the principal efforts of both George Glass and of Kok Heong McNaughton at Los Alamos as well as of U.T. graduate students.

Overview

The RHIC accelerator will collide relativistic heavy-ion beams (with up to 200 GeV energy in the center of mass for the nucleon-nucleon collision) in an attempt to create the quark-gluon plasma (QGP), an unstable state of unconfined gluons and quarks. This QGP, hypothesized by the MIT bag model and QCD lattice gauge theory [1], may be present at the center of neutron stars or have existed shortly after the Big Bang. In addition to heavy-ion collisions, proton-proton and proton-nucleus collisions will also be produced at RHIC to study systems of highly excited, very dense nuclear matter, hard QCD parton-parton scattering (with jet formation) on such systems, and proton-proton collision spin effects (at 500 GeV cm).

Detector design

Detectors for these experiments must track, identify, and momentum analyze a broad range of particles, including hyperons and strange mesons whose short lifetimes and subsequent decay lengths place difficult requirements on the detector design and construction. The STAR detector, one of two large collider detectors at RHIC, is a combination of a silicon vertex tracker (SVT), a time projection chamber (TPC), time of flight (TOF) counters, an electromagnetic calorimeter (EMC), and an external time projection chamber (XTPC), based around a solenoidal magnet. Supporting these devices will be a system of front-end electronics (FEE), a multi-level trigger, and data acquisition. Figure 1 shows a perspective view of STAR.

The source of spin in the proton has been a major issue recently, and direct photon detection would allow for some important measurements of spin dependence with polarized colliding protons that relate to the gluon spin structure function. Funds for engineering and prototyping for the electromagnetic calorimeter are being sought from DOE by John Harris and Tim Hallman within nuclear physics. The Argonne group, led by A. Yokosawa, has embarked on this phase of development for STAR. George Glass has been asked by John Harris, as well as by Hal Spinka of ANL, to join in this development effort, and will participate in the design, development, and fabrication of this calorimeter. The task ahead will require a serious engineering study with major prototyping and testing. Further, a major effort is needed for simulation studies that

would establish the detectability of the direct gammas and the associated jets within the plethora of tracks generated in the high luminosity environment anticipated for RHIC.

George Glass has participated in the Electromagnetic Calorimeter Working Group meeting at Argonne and the full collaboration meeting at Berkeley, both in February '93. He has also done calculations to determine whether a particular configuration of shower detectors would give adequate uniqueness to the determination of the pseudo-rapidity parameter. These calculations found that only ~40% of the events would satisfy the uniqueness criteria, and therefore the design was abandoned. Other preparations for involvement have been made by becoming familiar with ULTRIX, DEC's version of UNIX, which is the operating system of choice for STAR's computer simulations and data acquisition, and with GEANT, the standard simulation package.

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Figure 1: The STAR detector.

III. PERSONNEL WORKING ON PROJECT

Peter J. Riley, Professor of Physics

Kok Heong McNaughton, Computer Programmer (3/4 time)

Chau Nguyen, Postdoctoral, (1/2 time until August 31, 1993; full time starting September 1, 1993)

George Glass, Research Scientist (Starting Sept. 1, 1992)

David Ambrose, Graduate Student

Mark Bachman, Graduate Student, completed Ph. D. work September, 1993.

Patrick Coffey, Graduate Student

Bernard Jobst, Graduate Student, Graduated (M.Sc.) August, 1992.

Most of Peter Riley's time during 1991-1992 was spent on E1097 work, although he participated in E791 and E871 work at BNL. During 1993 he emphasized E876 (LAMPF) and E871 at BNL. Kok Heong McNaughton lives and works in Los Alamos, and has been responsible for the software for our experiments there. In addition, she has assisted in data acquisition runs, and in data analyses at LAMPF. Chau Nguyen works entirely on BNL E871, and there has concentrated his efforts on the lead glass array. He divides his time, as dictated by the experimental needs, between Austin and BNL. Half of his support is provided by this grant, and half by Jack Ritchie's grant. George Glass, who joined our group effective September 1, 1992, lives and works in Los Alamos. He has participated in all of our recent LAMPF experiments. During 1993 he has become involved in design studies for the electromagnetic calorimeter for STAR. However, since April, 1993, nearly all his time has been dedicated to the setting up and running of the LAMPF experiment E1293. This experiment took beam time from the end of July through September, and has now been completed. David Ambrose was responsible for the development of the E1097 tracking and event reconstruction software, as well as for much of the development work on the E1097 cylindrical drift chamber. Until November, 1992, he expected to base his Ph. D. research on LAMPF E1097. Since then he has joined E871 at BNL. He is responsible for much of the hardware/software for the new E871 muon hodoscope (μ HO). Mark Bachman, whose Ph. D. thesis research is based on TRIUMF E372, spent the past two years at U.T. Austin working on E372 data analyses. He has now completed his Ph. D. dissertation and has joined the U.C. Irvine group at BNL (under the direction of Bill Molzon) working on E871. Patrick Coffey graduated with a B.S. in physics in December, 1991, and then spent the first half of 1992 working at LAMPF on the E1097 drift chamber. He entered U.T. as a physics

graduate student in September, 1992. In January, 1993, he joined E871, and will base his Ph. D. research on the rare kaon decay experiment at BNL. He is presently working on the lead glass array for that experiment. Bernard Jobst, a foreign exchange student from Germany, completed his M.Sc. thesis during the summer of 1992 working with our group on E876 at LAMPF.

IV. PUBLICATIONS and ABSTRACTS

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ABSTRACTS

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V. TITLE PAGES of PUBLICATIONS

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