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Studies in Medium Energy Physics

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Abstract

This document constitutes the (1991 - 1994) technical Progress Report for the ongoing medium/high energy nuclear physics research program supported by the U. S. Department of Energy through Special Research Grant DE-FG05-88ER40444.

The experiments discussed were/are conducted at the Los Alamos National Laboratory's (LANL) Clinton P. Anderson Meson Physics Facility (LAMPF) and the Alternating Gradient Synchrotron (AGS) facility of the Brookhaven National Laboratory (BNL). Considerable design, fabrication, setup, testing, and support work was/is done at The University of Texas at Austin as part of the research program.

The overall motivation for the work done over the past three years was driven by four main objectives: (1) provide proton-nucleon and proton-nucleus scattering data which serve to facilitate the study of effective two-body interactions, test (and possibly determine) nuclear structure, and help study reaction mechanisms and dynamics; (2) provide unique, first-of-a-kind "exploratory" proton-nucleus scattering data in the hope that such data will lead to discovery of new phenomena and new physics; (3) perform precision tests of fundamental interactions, such as rare decay searches, whose observation would imply new physics; and, (4) begin work associated with the Solenoidal Tracker at RHIC (STAR) project at the Relativistic Heavy-Ion Collider (RHIC) and phase in major work associated with relativistic heavy ion physics.

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1 Introduction

This document is a 1991 - 1994 progress report for research projects in medium/high energy nuclear physics that have been supported by the U. S. Department of Energy through Grant No. DE-FG05-88ER40444. University of Texas personnel who have worked on these projects during the 1991-1994 period are G. W. Hoffmann (Professor); R. L. Ray (Research Scientist); A. Green and J. E. McDonough (post-doctoral fellows); W. Betts, X. Chen, P. Jensen, E. Paganis, M. J. Purcell, D. M. Read, and S. D. Worm (Graduate Students); S. Thompson (Undergraduate Student).

For this report period the overall scope of the research program contained four general components, as described in the paragraphs below. The individual projects, as discussed in detail in this document, fit into this overall scheme. The work includes completed projects as well as continuing projects which will extend beyond 1994.

Since 1975 one of the sustained goals of our research program has been to provide precision medium energy proton-nucleon and proton-nucleus scattering data, as well as pragmatic, state-of-the-art analyses, which serve to facilitate the systematic study of effective two-body interactions, to test (and possibly determine) nuclear structure, and to help study reaction mechanisms and dynamics. It is fair to say that, today, reasonably quantitative descriptions of a vast amount of data for energies between 100-1000 MeV, and nuclei spanning the periodic table, are obtained using a variety of microscopic models [both relativistic and nonrelativistic] which are built up from first principles. Our review article in *Physics Reports* describes this research effort. Some of the work done during the 1991-1994 period was the natural continuation of this very successful program. One example of recent work in this area is our precision (1%) forward-angle proton-nucleus elastic scattering experiment which provides cross section data in the Coulomb-nuclear interference region; the relativistic and nonrelativistic models give cross sections in this region whose differences are typically 15-25%.

Another fruitful part of our research program consists of unique, first-of-a-kind, "exploratory" $p + A$ experiments which are done to search for new, unexpected phenomena and new physics, and which provide data to stimulate further theoretical work. A recent example is our 500 MeV $\vec{p} + {}^{13}\vec{\text{C}}$ experiment which used, for the first time, a polarized nuclear target. Such experiments add a new spin degree of freedom to the scattering problem. In 1988 we decided to build a small compact refrigerator so that we could continue these experiments without the very large overhead associated with using the standard large volume polarized targets commonly in use. This construction project is essentially complete and the evaporation refrigerator is ready for testing and commissioning as the core of a dynamically polarized target setup. Commissioning of the target will occur in Spring 1994 at the

Triangle Universities Nuclear Laboratory (TUNL), and the target will be first used at TUNL for low energy neutron scattering experiments. This target is portable and can easily be moved to other facilities for experiments after the TUNL work is complete.

Several years ago we recognized that our collaborators in the field of medium energy physics were beginning to pursue interests other than the *traditional nuclear physics* efforts of the types discussed in the above two paragraphs. This is owing, of course, to the fact that medium energy facilities, such as LAMPF, TRIUMF, and IUCF have been in operation for decades, and much of the more interesting physics research opportunities that can be pursued at these facilities have been explored. Thus, although we continued to pursue some very exciting aspects of research associated with our traditional $p + A$ program discussed above, we directed some of our resources to new initiatives that are expected to be in the mainstream of medium/high energy nuclear physics in the future.

One new initiative concerns the study of fundamental interactions—more and more this area of research has become recognized as a very important and vital branch of research in medium energy physics. Measurements performed in the past few years make it clear that any possible incompleteness of our present understanding of fundamental interactions must originate with physics at very large mass scales. In 1988 we broadened our research program to include an experiment at the AGS which searched for the forbidden decay $K_L^0 \rightarrow \mu e$ and the suppressed decay $K_L^0 \rightarrow ee$. One result of this experiment is the smallest upper limit to date for each of these unobserved decays. A new experiment (with more than an order of magnitude improvement in sensitivity) was designed, proposed, and approved. Its purpose is to improve the single event sensitivity for $K_L^0 \rightarrow \mu e$ to less than 1×10^{-12} , and if no events are observed, will set an upper limit on the branching ratio of about 2×10^{-12} . The new experiment should also see a few $K_L^0 \rightarrow ee$ if this process occurs at the expected level. The new experiment will also observe about 10,000 $K_L^0 \rightarrow \mu\mu$ decays. A novel feature of the new experiment is a “high tech” beam plug inside one of the detector’s dipole magnets to stop neutral beam. Three beam plug development and test runs occurred between 1990 - 1992. An engineering run for this experiment occurred in Spring-Summer 1993. Production runs will start in 1994. Our group has major responsibility for the beam plug, the instrumented muon filter, and the level 1 trigger of this new experiment.

During this report period, our group made the decision that our long term interests were in the kinds of physics that could be done at the new Relativistic Heavy Ion Collider (RHIC) facility under construction at the Brookhaven National Laboratory. We joined the STAR Collaboration in September 1992. We have become actively involved with the Silicon Vertex Tracker (SVT) group and have done work associated with testing the silicon drift detectors (SDD’s), built a computer controlled test beam apparatus for precision in-beam testing of the SDD’s, have responsibility for the data acquisition associated with both testing SDD’s and for the SVT of STAR, and have done software work associated with vector matching

of SVT trajectories with those from STAR's Time Projection Chamber (TPC). We have also started some significant construction projects for parts of the TPC. Two of our graduate students spent the Summer (1993) at LBL contributing to the TPC Research and Development effort. In the future we hope to provide a strong contribution to the data acquisition effort of STAR. Dr. J. J. Schambach will join us in January and will lead this effort.

Our group has authored 23 refereed journal articles, 7 published conference proceedings, 11 e871BNL technical reports, and 14 abstracts during the 1991-1994 research period.

The material contained in this document summarizes the highlights of our 1991-1994 research program.

2 Nucleon-Nucleon and Nucleon-Nucleus Experiments at LAMPF

2.1 EXP392: Measurement of the Wolfenstein Parameters for $p + p$ and $p + n$ ($p + {}^2\text{H}$ and $p + {}^{12}\text{C}$) Scattering at 500 and 800 MeV

(M. Barlett, G. W. Hoffmann, L. Ray; LANL;
G. W. Hoffmann, spokesman)

Summary: Analyzing powers (A_y) and polarization transfer parameters (D_{SS} , D_{SL} , D_{LS} , D_{LL} , D_{NN}) for 500 MeV $\bar{p} + {}^2\text{H}$ and $\bar{p} + {}^{12}\text{C}$ inclusive quasielastic scattering at 10° , 15° , and 20° laboratory scattering angles, were determined. The $\bar{p} + {}^2\text{H}$ data are consistent with the isospin-average of the proton-proton and proton-neutron scattering observables whereas the $\bar{p} + {}^{12}\text{C}$ data are not. A relativistic plane wave impulse approximation calculation leads to better agreement with the $\bar{p} + {}^{12}\text{C}$ spin-observables.

Medium energy proton-nucleus quasielastic polarization transfer data are sensitive to the double spin-flip parts of the effective two-body interaction. Careful analyses of such data within the context of either the nonrelativistic multiple scattering approach or the relativistic Dirac equation model may allow new, precision tests of the nuclear continuum response and the effective projectile-nucleon interaction.

The data discussed here were taken at LAMPF (EXP392) using the HRS and its focal plane polarimeter (FPP) and are reported in Ref. 1. The 500 MeV $\bar{p} + {}^2\text{H}$ data were taken using a liquid deuterium target² and the ${}^{12}\text{C}$ data were taken using a 150 mg/cm² solid target. Data were obtained at laboratory scattering angles of 10° , 15° , and 20° at the maximum of the quasielastic peak (i.e. the HRS magnetic fields were set at each angle so that the spectrometer central momentum corresponded to that for 500 MeV $p + \text{nucleon}$ elastic scattering at that angle). The subsequent momentum transfers and energy-losses for the scattered proton in the laboratory are 0.96, 1.4 and 1.9 fm⁻¹, respectively, and 19, 42 and 72 MeV, respectively. The HRS angular acceptance in the plane of scattering is approximately 2° , and the HRS momentum acceptance is approximately 2%. Further experimental details are reported in Refs. 2 and 3.

The data are presented in Fig. 1 as a function of the corresponding free nucleon-nucleon (NN) center-of-momentum scattering angles. The quoted errors in the observables are statistical only; other sources of error are discussed in Ref. 4 and

are believed to be small. The solid curves represent predictions of a simple isospin-weighting model which uses the Arndt SP89 phase shift solution. In this model the $\bar{p} + \text{nucleus}$ quasielastic spin-observables are assumed to be the cross section-weighted average of the free $p + \text{nucleon}$ spin-observables without Fermi motion averaging. Since $N = Z$ for both ^2H and ^{12}C , the model predictions are the same for both nuclei. Except for D_{LL} the solid curves are in good agreement with the ^2H data as expected. However, they do not agree with the ^{12}C data.

The dashed and dotted curves in Fig. 1 are the results of relativistic plane wave impulse approximation calculations for 500 MeV $\bar{p} + ^{12}\text{C}$ quasielastic scattering.⁵ The RPWIA model uses the relativistic impulse approximation form of the free nucleon-nucleon Lorentz invariant scattering amplitude, the plane wave approximation for the scattered proton wave function, and the relativistic Fermi gas model for the target. Relativistic dynamical effects are included in an approximate manner by increasing the strength of the lower components of the Dirac spinors (relative to the free particle value) using a parametrized effective mass. The effective mass is taken to be the free nucleon mass plus the scalar potential; the latter is evaluated at an average nuclear density determined by the density distribution and the transmission probability for a medium energy proton projectile.⁵ The dashed curves in Fig. 1 are results with both effective projectile-nucleon mass (M_1) and effective target nucleon mass (M_2) equal to the nucleon mass (M). The dotted curves in Fig. 1 result from using $M_1 = 0.91M$ and $M_2 = 0.87M$. Further details of this RPWIA model are given in Refs. 5 and 6.

As seen in Fig. 1, the A_y and D_{SS} predictions are more sensitive to relativistic enhancement of the lower components of the Dirac spinors than are the other observables. The RPWIA predictions with enhanced lower components show excellent agreement with A_y and generally provide somewhat improved descriptions of the D_{ij} data, although the D_{LL} datum and the D_{SS} data differ markedly from both curves. The shapes of the angular distributions for A_y , D_{NN} and D_{SL} are reproduced fairly well, whereas that for D_{SS} is not. Similar results discussed in Ref. 5 suggest that most of the reduction in A_y is due to relativistic effects in the projectile wave function ($M_2=M \neq M_1$). The same model predicts more sensitivity to relativistic effects in the target wave function for some of the polarization transfer parameters.

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Figure Caption

Figure 1: The 500 MeV $\bar{p} + {}^2\text{H}$ (circles) and $\bar{p} + {}^{12}\text{C}$ (squares) inclusive analyzing powers (A_y) and polarization transfer (D_{ij}) parameters at the quasielastic peak as a function of the corresponding free NN center-of-momentum scattering angles. The solid curves indicate the predictions of the isospin-averaging model. The dashed (dotted) curves represent the results of RPWIA calculations assuming free particle (dynamically enhanced) lower components of the Dirac spinors. The RPWIA calculations were only done for 10° , 15° and 20° laboratory angles; the dashed and dotted lines simply connect the three values. Errors in the data include only statistical contributions.

Figure 1

2.2 EXP955: Polarized Proton Elastic Scattering from Polarized ^{13}C and ^1H

(G. W. Hoffmann, M. L. Barlett, W. Kielhorn, G. Pauletta,
M. Purcell, L. Ray; LANL; NMSU; Minnesota; ASU; OSU; IBM;
G. W. Hoffmann, R. L. Ray, M. L. Barlett, J. Jarmer, spokesmen)

Summary: 500 MeV $\vec{p} + \vec{p}$ elastic $A_{00\text{NN}}$ data were taken during the $\vec{p} + ^{13}\vec{\text{C}}$ experiment. These very high precision, forward-angle data show a 5-10% normalization discrepancy with recent results from phase shift analysis.

Although the isospin (I) = 1 nucleon-nucleon elastic channel supposedly is well determined for incident energies up to 800 MeV, investigation of the NN data base near 500 MeV reveals sparse forward angle data for spin observables which depend upon target polarization.¹ An example is the spin correlation parameter $A_{00\text{NN}}$ for $p + p$ scattering near 500 MeV.

As part of LAMPF EXP955 we obtained high precision, forward angle spin correlation data $A_{00\text{NN}}$ for $\vec{p} + \vec{p}$ elastic scattering at 497.5 MeV from 23.1° to 64.9° in the NN c.m. These new $A_{00\text{NN}}$ extend to more forward angles and have significantly improved statistical accuracy than those from other experiments. The new results should be used to provide tighter constraints on the $I = 1$ NN spin-dependent amplitudes in the forward angle region; this in turn will permit more realistic phenomenological input for the nucleon-nucleus reaction calculations and will provide better empirical constraints for meson exchange models of the NN interaction.

Full descriptions of the polarized target and the polarized proton scattering experiment are given elsewhere.^{2,3} Target polarization direction was reversed every 8-16 hours and ^1H polarization was typically 50-80% during the course of the experiment. Beam polarization was determined via quench-ratio measurements and by a beam line polarimeter located immediately upstream of the target. Beam polarization was typically 80% and was reversed every 2 min. The HRS momentum analyzed protons elastically scattered from ^1H . The typical missing mass spectrum for elastic $p + p$ consisted of a sharp peak (typically, 2.5 MeV, FWHM) on a smooth, flat background from quasielastic scattering. The elastic yields were extracted with negligible error.

The proton yield for elastic $p + p$ can be expressed as

$$Y = \sigma_0(N_A\rho t)[I_0(\Delta\Omega)\epsilon][1 + P_B A_{00\text{N}0} + P_T A_{00\text{N}0} + P_B P_T A_{00\text{NN}}], \quad (2.1)$$

where σ_0 is the $p + p$ unpolarized differential cross section, $(N_A\rho t)$ is the number of target protons per unit area, P_B and P_T are the appropriate (average) beam and target polarizations, and the quantities I_0 , $\Delta\Omega$ and ϵ represent the number of incident beam protons, the HRS solid angle, and the overall efficiency, respectively.

Subscript N refers to direction $\hat{n} = (\vec{k} \times \vec{k}')/|\vec{k} \times \vec{k}'|$ where $\vec{k}$ ($\vec{k}'$) is the initial (final) relative momentum. Four equations of the above form result corresponding to the various combinations of beam and target polarization orientations (“up” or “down” for each).

In general the magnitudes of P_B and P_T , and the effective target thickness can be different between the target “up” and “down” runs. The latter is caused by beam drift on the cylindrical target flask and the inherent inhomogeneity of the frozen target material; however, variations were generally $\leq 1\%$ as determined during the very careful analysis of the polarized ^{13}C data.² For the analysis reported here we solved the above equations for target polarization “up”, target polarization “down”, and A_{00NN} . The known values of $A_{000N} = A_{00N0} \equiv A_y$ were taken from Ref. 4.

Errors associated with previously reported^{1,5} values of A_{00NN} for $p+p$ at energies near 500 MeV are typically $\pm 0.03 - 0.06$ for angles forward of 50° c.m. The A_{00NN} reported here are consistent with those of Bystricky *et al.*,⁵ at 494 MeV (closest in beam energy) in the overlapping angular region; our new values are listed in Table I. The errors quoted vary from ± 0.01 to ± 0.04 and include *both* statistical and systematic effects. The new A_{00NN} extend the angular range of the ~ 500 MeV A_{00NN} data base to more forward angles by about 10° . More importantly is the factor of 2-3 improvement in the statistical quality of the new data.

The data from the present experiment (solid dots) are shown in Fig. 1 in comparison with those of Bystricky *et al.*⁵ (crosses) and with the most recent phase shift solutions of Arndt *et al.*¹ (solution SM92, solid curve), Bugg⁶ (1990, dashed curve), and with an older Arndt phase shift solution (SP89, dotted curve). The present data are *not* included in the data bases used in any of these phase shift analyses. In the angular region forward of 40° c.m. the predictions of each phase shift analysis are somewhat larger in magnitude (about 5-10%) than the data. All three predictions are in good agreement with the data at angles larger than 40° c.m.

In light of the fact that the overall systematic normalization uncertainty for the present data is ± 0.01 , the 5-10% discrepancy at forward angles is significant. The quality of these new data with respect to statistics and systematic errors should prove useful in constraining phase shift analyses in the future and in determining more accurate NN spin-dependent amplitudes for use in theoretical analyses of nucleon-nucleus scattering.

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Figure Caption

Figure 1: A_{00NN} results from LAMPF EXP955 (solid dots) are compared with those of Bystricky *et al.* (crosses, Ref. 5) and predictions of several phase shift analyses: Arndt (SM92) – solid curve; Arndt (SP89) – dotted curve; Bugg (1990) – dashed curve.

Table I: Spin correlation parameter, A_{00NN} , for proton + proton elastic scattering at 497.5 MeV incident proton kinetic energy from LAMPF EXP955. Errors include statistical and systematic uncertainties.

$\theta_{c.m.}$ (deg)	A_{00NN}	ΔA_{00NN}
23.1	0.197	0.012
26.2	0.316	0.016
29.3	0.401	0.019
32.7	0.472	0.022
35.8	0.533	0.024
38.6	0.539	0.024
46.7	0.609	0.032
53.5	0.631	0.038
62.2	0.550	0.040
64.9	0.549	0.046

Figure 1

2.3 EXP1079: $p + A$ Precision Elastic Forward Angle Cross Sections

(W. Betts, G. W. Hoffmann, L. Ray, D. Read, S. Thompson; LANL; Georgia; Rutgers; G. W. Hoffmann, J. F. Amann, spokesmen)

Summary: The development and construction phase of this 1% absolute differential cross section experiment for $p + A$ elastic scattering was completed in Summer 1991. The production run occurred during Summer 1992 when 500 MeV $p + {}^{40}\text{Ca}$ data were taken over the laboratory angular range ($1.75^\circ - 4.4^\circ$). Analysis of these data is in progress.

A comparison of observables predicted by scattering models which use either relativistic (RIA) or nonrelativistic (NRIA) dynamics indicates¹ significant differences in the magnitudes of the 500-800 MeV $p + {}^{16}\text{O}$, ${}^{40}\text{Ca}$, ${}^{208}\text{Pb}$ differential cross sections in the forward-angle, Coulomb-nuclear interference region (see Fig. 1). At 500 MeV some of the differences are 15-25%. This result is stable with regard to uncertainties in the theoretical calculations ($\pm 2-6\%$) including that due to medium effects. It has also been pointed out that precise cross section data in the Coulomb-nuclear interference region would set important constraints on relativistic models of the Lorentz invariant amplitudes and the scalar densities of the target nucleus.

The first phase of EXP1079 was to develop the techniques required for a 1% experiment. Of particular importance are accurate integrated beam flux determination (0.5%), precise polar scattering angle determination (0.001°), and accurate solid angle determination (0.1%).

During development runs spanning 1990 - 1991 we commissioned the new HRS Faraday cup, a high gain (xenon-ethane 600 mm Hg) ion chamber, a beam counting scintillator telescope, and the new Line C inductive pickup coil (LCCM). We demonstrated that with care there is sufficient overlap in the beam intensity regions over which these devices operate that together they can redundantly determine beam current over the dynamic range of $10^4/\text{s}$ to several nA with better than 1% absolute accuracy.

We demonstrated that the solid angle can be determined to the 0.1% level using precision machined slits of aperture 50% of the HRS acceptance. Slit edge scattering was demonstrated to have negligible effect on the solid angle defined by the aperture (note that medium energy protons that go through the slit material lose about 10 MeV so that they are shifted in the missing-mass spectrum generated by the HRS; nominal HRS resolution is 100 keV).

We designed beam scanning scintillators which step through the beam to accu-

rately provide the integral $\int_0^x I(x)dx$, where $I(x)$ is the beam intensity at transverse position x . These scintillators are 1 in. by 1 in. by 1 mm, and are coupled to EMI9813B photomultipliers. Specially designed tube bases which operate in vacuum allow these tubes to operate between 200 V and 2000 V, providing an effective gain dynamic range of 10^9 . The system was designed for beams of a few kHz up to about 10 GHz. The beam scanners are mounted on linear slides and the positions are determined to 0.0002 in. using Heidenhain optical encoders (see Fig. 2). These linear encoders measure light that is transmitted through a glass diffraction grating. When the grating is moved relative to the scanning unit, the lines and spaces of the scale alternately coincide with those of the index gratings. The corresponding fluctuations of the light are sensed by photocells, which generate two sinusoidal output signals, which are phase-shifted 90 degrees relative to each other. These signals are then interpolated and converted to square waves with a Schmitt trigger. The 90 degree phase shift between the signals allows for four signal edges which can be used to determine the direction of the motion.

The performance of these beam scanners was carefully evaluated during a test run in Summer 1991. A Line C (HRS) pencil beam was prepared using the Line C collimators. For the 1991 run the FWHM of the beam was determined to be about 0.010 in. and the centroid position was determined to 0.001 in. The beam profile during this run was typical of that required for the most forward angle part of the experiment.

A considerable amount of effort from 1990 - 1992 went into the design, mechanical construction, testing and commissioning of the actual EXP1079 apparatus which we used for the production runs in summer 1992. About two man-years of machine shop work has been provided for this project by the Physics Department machine shop. The system, whose components are all remotely moveable via computer control, are each mounted on an aluminum tooling plate that fits inside the HRS scattering chamber (Fig. 3). The components consist of 4 beam scanners (an xy pair before and after the target, separated by about 30 in.), 2 high gain ($\times 1000$) ion chambers, 3 beam counting scintillators (for low intensity beams), a new target ladder, and a moveable, precision slit system made of tool steel with tapered apertures of constant polar scattering angle (Figs. 4-6) are photographs of the apparatus. The reference positions of the beam scanners, the target, and the slit apertures are determined using an aligning procedure to an accuracy of about 0.001 in. The optical encoders then give relative positions to an accuracy of 0.0002 in. A special glove box (which attached to the side of the HRS scattering chamber, see Fig. 7) to allow mounting of the targets in an inert atmosphere was designed and constructed at Texas.

The initial physics production run occurred during Summer 1992. Approximately 2 months were devoted to aligning, calibrating, checking, and cross checking the various pieces of the apparatus. Physics data were taken between 26 July, 1992 - 5 August, 1992. A sufficient amount of data were accumulated for the important angular range $1.75^\circ - 4.41^\circ$ for $p + {}^{40}\text{Ca}$ such that the statistics for 0.5°

angle binning should be less than 0.5%. Fig. 8 shows the results of typical beam scans associated with these forward angle runs. Fig. 9 shows how the full energy elastic peak in the missing mass spectrum allows us to determine which elastic protons passed through the slit aperture. In Fig. 10 are shown the calculated “true” scattering angle with “test” on “good event only” (10a) and “good event and good missing mass in full elastic energy region” (10b). The sharp edges in Fig. 10b are consistent with the angular resolution provided by the HRS system itself.

Based on the online data and the consistency checks made during the experiment, we expect that the data should have an absolute normalization error of about 1-2%. Analysis of these data has proceeded slowly owing to deadlines that have had to be met in connection with AGS E871 and some STAR projects.

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Figure Captions

Figure 1: Uncertainty bands for the forward angle differential cross sections for 500 MeV $p + {}^{40}\text{Ca}$ and ${}^{208}\text{Pb}$ from the standard NRIA (shaded bands between dashed curves) and RIA (shaded bands between the solid curves) models (from Ref. 1).

Figure 2: Schematic of Heidenhain optical encoder.

Figure 3: Photograph taken during first installation of preliminary EXP1079 apparatus into HRS scattering chamber.

Figure 4: Photograph of EXP1079 apparatus taken from beam left showing the first horizontal and vertical beam scanners. The scintillators are housed in stainless steel cans with thin aluminized mylar windows covering the end 2 cm of each scintillator.

Figure 5: Photograph of EXP1079 apparatus looking down the beam axis into the HRS scattering chamber.

Figure 6: Photograph of EXP1079 apparatus from beam exit side of HRS scattering chamber showing movable slits and beam counting scintillators.

Figure 7: Photograph of glove box attached to side of HRS scattering chamber that allowed target installation in inert (argon) atmosphere.

Figure 8: Typical beam profiles as determined during the experiment using the beam scanners discussed in the text.

Figure 9: A missing mass spectrum for 500 MeV $p + {}^{40}\text{Ca}$ at a central HRS scattering angle of 2.0° . The sharp peak corresponds to elastic protons that went through the slit aperture, while the broad bump a few MeV below it corresponds to those elastic protons that went through the slit material.

Figure 10: Calculated polar scattering angle for 500 MeV $p + {}^{40}\text{Ca}$ gated on "good event only" (10a) and "good event and good elastic missing mass" (10b) at a central HRS scattering angle of 2.0° .

Figure 1

Figure 2

Figure 3

Beam Scanners

Figure 4

Target Ladder

Beam Scanner

Figure 5

Target Ladder

Figure 8

4-AUG-1992 16:33:50.44---HMASS --CORE

Figure 9

Figure 10

2.4 EXP1205: Precision Measurement of D_{NN} for $^{13}\text{C}(\vec{p}, \vec{p})$ at 500 MeV

(G. Hoffmann, M. Barlett, L. Ray, D. Read, S. Worm;
LANL; Rutgers; Georgia; Ohio State;
G. W. Hoffmann, J. F. Amann, C. Glashauser, spokesmen)

Summary: The high resolution spectrometer (HRS) and its focal plane polarimeter (FPP) were used to make precision measurements of the polarization transfer quantity D_{NN} for 500 MeV polarized proton elastic scattering from ^{13}C . Theoretical analysis of these data will provide information about specific components of the NN effective interaction and will impose important, new constraints on relativistic and nonrelativistic scattering models. Measurements were made in the angular region of the first diffractive minima of the differential cross section (around 16° laboratory angle). Using a ^{13}C - ^{12}C mixed target, data for $p + ^{12}\text{C}$ were taken simultaneously with the ^{13}C data in order to empirically eliminate systematic errors. Data analysis is still in progress.

The principal goals of intermediate energy proton-nucleus scattering experiments are to provide data which facilitate the study of the effective two-body interaction in nuclei, the determination of nuclear structure, the study of reaction mechanisms at medium energies, and the testing of relativistic and nonrelativistic scattering theories.¹⁻⁴ The largest effort in this field has involved proton elastic and inelastic scattering from even-even target nuclei. Analyses of these data have been aimed at studying the dominant, isoscalar non-spin-transfer components of the NN force, the isoscalar ground state matter densities and collective transition densities, and comparing relativistic and nonrelativistic scattering models. Quantitative, parameter free descriptions of proton-(spin-zero)nucleus elastic scattering and inelastic excitation of natural parity, collective states, using either the relativistic or nonrelativistic models, are gradually becoming a reality.^{5,6}

Much less work has been done for reactions involving spin and/or isospin transfer. These reactions are sensitive to the spin-transfer and isovector components of the NN force and to single particle aspects of nuclear structure. At intermediate energies, work on these topics includes $(\vec{p}, \vec{p}')$ for non-natural parity transitions, (p,n) charge-exchange at 500 MeV on ^{15}N , 500 MeV $\vec{p} + ^{13}\vec{\text{C}}$ elastic scattering analyzing power A_{000N} and spin correlation parameter A_{00NN} ,⁷ and D_{NN} at 500 MeV for $^{13}\text{C}(\vec{p}, \vec{p})$ elastic scattering⁸ (see Fig. 1). Relativistic and NR models describe the inelastic data with varying success, with no clear preference for either one.⁹ Neither approach is able to describe the charge-exchange data,¹⁰ while both approaches provide reasonable, qualitative descriptions of the polarized ^{13}C elastic scattering data.⁷ The existing elastic D_{NN} data (see Fig. 1) for ^{13}C are of insufficient quality to test reaction models or effective interactions. In general, our

present understanding of spin and isospin transitions at intermediate energies is unsatisfactory.

A precision measurement of D_{NN} for proton elastic scattering from ^{13}C enables new tests of relativistic and nonrelativistic models and provides effective interaction information that complements that obtained from the elastic $\vec{p} + \hat{n}$ -type polarized ^{13}C data and from $(\vec{p}, \vec{p}')$ data. The presently available D_{NN} elastic scattering data from odd nuclei include only 72 MeV and 500 MeV $^{13}\text{C}(\vec{p}, \vec{p})$ data and 65 MeV $^{15}\text{N}(\vec{p}, \vec{p})$ data. The low energy data^{11,12} are not suitable for studies of the relativistic versus nonrelativistic approaches. The existing 500 MeV data are not of sufficient quality for studying the effective interaction or relativistic versus NR issues.

The principal advantages of this method of studying the relativistic versus nonrelativistic question and determining the spin-transfer components of the NN effective interaction are: (1) The nuclear structure uncertainties are minimized for elastic scattering relative to (p, p') ; the polarized ^{13}C data can be used to help "fine tune" the valence wave function. (2) These measurements address much of the same physics (*i.e.*, PS versus PV forms, strength of the pseudoscalar invariant, lower component enhancement, etc.) as in the $\hat{s}$ -type polarized ^{13}C elastic scattering experiment but are obviously much easier to do.

The quantity D_{NN} for elastic scattering from even-even ($J^\pi = 0^+$) targets is unity, corresponding to spin-flip probability zero. For ^{13}C with ground state $J^\pi = \frac{1}{2}^-$ both $\Delta J = 0, 1$ contributions are allowed. $\Delta J = 1$ permits D_{NN} to differ from unity. The 500 MeV $\vec{p} + ^{13}\text{C}$ spin-flip probability was predicted using the RIA-DWBA model of Ref. 4 and a NRIA-DWBA model. For the relativistic model the form taken for the Lorentz invariant NN effective interaction is the local form,

$$F = F_S + F_P \gamma_1^5 \gamma_2^5 + F_V \gamma_1^\mu \gamma_{2\mu} + F_A \gamma_1^5 \gamma_1^\mu \gamma_2^5 \gamma_{2\mu} + F_T \sigma_1^{\mu\nu} \sigma_{2\mu\nu}. \quad (2.2)$$

The proton-nucleus scattering amplitude in the DWBA approximation is given by⁴

$$f_{m', \mu'; m, \mu}(\vec{k}, \vec{k}') = f_{m', m}^{core}(\vec{k}, \vec{k}') \delta_{\mu' \mu} - \frac{m}{2\pi(\hbar c)^2} \langle \chi_{c, \vec{k}', m'}^{(-)} | u_{nlj\mu'} F | u_{nlj\mu} \chi_{c, \vec{k}, m}^{(+)} \rangle, \quad (2.3)$$

where f^{core} is the elastic scattering amplitude from the (^{12}C) core, $u_{nlj\mu}$ is the relativistic bound state wave function ($1p_{\frac{1}{2}}$, neutron), and $\chi_{c, \vec{k}, m}$ is the relativistic, 4-component distorted wave function for the core nucleons corresponding to f^{core} . The bound state wave function, $u_{nlj\mu}(\vec{r})$, contains upper and lower components, ϕ and λ , respectively, and for the purpose of studying sensitivities was assumed to be a simple $1p_{\frac{1}{2}}$ eigenstate of the relativistic mean field¹³ (RMF) potential for ^{12}C . For some of the calculations discussed here the nonrelativistic limit of λ was used. This limit was obtained by solving the single particle bound state Dirac equation in the limit of zero scalar and vector binding potentials. Pseudovector (PV) rather than pseudoscalar (PS) forms for the Lorentz invariant NN interaction were also used.⁴

The five invariant amplitudes in Eq. (2.2) were obtained from the Pauli representation of the NN scattering amplitudes by the transformation described in Ref. 3, using Arndt's SP82 phase shift solution. The relativistic distorted waves and core scattering amplitudes were generated from either the RIA - Dirac equation model³ for $p+^{12}\text{C}$ or the Dirac phenomenological optical model fit to the $p+^{12}\text{C}$ 500 MeV elastic scattering data (see Ref. 8).

For the nonrelativistic predictions the DWBA model of Ref. 4 was used. The same NN phase shifts were used as in the relativistic calculations. The $1p_{1/2}$ valence neutron wave function was taken to be the same as the upper component in the relativistic valence nucleon wave function. The core amplitudes and distorted waves were obtained from the Schrödinger equivalent optical potential of the Dirac phenomenological fit to the $\bar{p}+^{12}\text{C}$ elastic scattering data by solving the Schrödinger equation with relativistic kinematics.

In Fig. 1 RIA-DWBA predictions are shown with the existing D_{NN} data for $\bar{p}+^{13}\text{C}$ at 500 MeV. The curves are discussed in detail in Ref. 8. Briefly the solid and dashed lines resulted from using PV and PS forms for the NN invariant amplitudes, respectively. The curves in the upper (lower) half of the figure resulted from using the RIA (Dirac phenomenological) optical potential to generate the relativistic distorted waves and core scattering amplitudes. In Fig. 2 the sensitivity of the RIA-DWBA model predictions for D_{NN} to the lower component of the $1p_{1/2}$ bound state wave function is displayed. The solid and dashed curves were generated by using the RMF and NR limit for the lower component, respectively. Both calculations assumed the pseudoscalar form for the NN invariant amplitudes and the RIA model for the distorted waves and core amplitudes. In Fig. 3 nonrelativistic and relativistic predictions are compared. Dirac phenomenological optical potentials were used to generate the distorted waves and core scattering amplitudes. The shaded band encompasses the relativistic predictions while the dashed curve indicates the NR result.

In the language of the Lorentz invariant form of the NN interaction, the spin-flip probability for this case is determined primarily by the PS invariant and to a lesser extent by the space-like tensor component. It is particularly sensitive to the choice of PS or PV forms (if λ^{RMF} is assumed and not λ^{NR}). In contrast, for elastic scattering from polarized targets, the PS component is not important for the $\hat{n}$ -type polarized ^{13}C observables;⁴ its study requires the much more difficult experiment involving an $\hat{s}$ -type polarized target.⁴ It is also sensitive to the lower component strength of the valence wave function (for the PS form) (Fig. 2). There are also significant differences predicted between the NR model and the centroid of the range of the relativistic model predictions as shown in Fig. 3.

The predicted spin-flip strength is affected somewhat by the assumptions for the core scattering amplitude. This quantity can, however, be tightly constrained in the analysis, since precision unpolarized $\bar{p}+^{13}\text{C}$ data have been obtained. The dependences on the distorted wave model and the large, upper component of the valence wave function are weak. Multistep contributions in the region of the first

minimum can be evaluated using a Dirac coupled-channels code¹⁴ which includes the full proton + odd-nucleus relativistic optical potential.

It is crucial to the experiment to have well-resolved elastic peaks for ^{12}C and ^{13}C for accurate determination of the D_{NN} . Near a laboratory scattering angle of 16° (corresponding to center-of-momentum scattering angles near 18° for 500 MeV $p+^{12,13}\text{C}$), the elastically scattered protons from 500 MeV $p+^{12,13}\text{C}$ differ in energy by 300 keV. Simultaneous $p+^{13}\text{C}$ and $p+^{12}\text{C}$ data acquisition allows systematic errors to be removed in the experiment, since $D_{\text{NN}} = 1$ for ^{12}C .

Data were taken in September 1992. Individual 50 mg/cm² ^{12}C and ^{13}C targets were sandwiched to allow data to be taken simultaneously for both nuclei. An overall HRS resolution of about 130-180 keV was achieved as shown in Fig. 4. The experiment took physics data for about 1 week at one HRS central angle setting (16°). Replay of the data tapes is almost finished, and final analysis of the data should be completed shortly. The statistical error in the final D_{NN} (with 0.5° angle binning) will be about (± 0.02). Our preliminary results indicate that D_{NN} for both target nuclei is consistent with 1.00.

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Figure Captions

Figure 1: Data and RIA-DWBA predictions for D_{NN} for 500 MeV $\vec{p} + {}^{13}\text{C}$ elastic scattering from Ref. 8. The curves are discussed in the text.

Figure 2: Predicted sensitivity in D_{NN} to the lower component of the $1p_{\frac{1}{2}}$ bound state $\lambda(r)$ in the RIA-DWBA model (from Ref. 4). The curves are discussed in the text.

Figure 3: Relativistic and nonrelativistic DWBA predictions for 500 MeV ${}^{13}\text{C}(\vec{p}, \vec{p}) D_{NN}$. The shaded band indicates the range of predictions of the relativistic DWBA model. The upper (lower) limit of the shaded band corresponds to the PV (PS) form for the NN invariant amplitude. The NR prediction is indicated by the dashed curve.

Figure 4: Typical missing mass histogram taken with the HRS showing the resolved peaks for $p + {}^{12}\text{C}$ and ${}^{13}\text{C}$ elastic scattering.

Figure 1

Figure 2

p + ^{13}C 500 MeV; RIA vs NRIA

Figure 3

Figure 4

3 Polarized Nuclear Target Project

(G. Hoffmann; LANL)

Summary: A copy of the PSI polarized nuclear target refrigeration system has been made at The University of Texas at Austin for use in low and medium energy polarized-nucleon + polarized-nucleus (or nucleon) scattering experiments. Initial cooldown of the system was successful and further testing/development is in progress.

For some time, our group has had interest in exploring what new physics can be learned through use of polarized nuclear targets in low and medium energy scattering experiments. As an initial step in the realization of such experiments, we polarized ^{13}C and ^{19}F using dynamic nuclear polarization techniques (DNP).^{1,2} The ^{13}C work lead to the development of the polarized target constructed at LAMPF³ and used for EXP955, EXP1023, and EXP1025. This target was fabricated from one of the LAMPF setups originally designed to provide a polarized proton target for the LAMPF nucleon-nucleon program. Physically this setup (cryostat, plus supporting equipment such as vacuum pumps, dewars, NMR hardware, microwave hardware, etc.) was large, and considerable manpower and overhead was required in its use for $p + \text{nucleus}$ and $\pi + \text{nucleus}$ scattering experiments (several months setup/checkout time).

For the past 15 years the PSI group in Switzerland headed by S. Mango has been developing compact ^3He evaporation/ ^3He - ^4He dilution refrigerators for use with the polarized proton/deuteron experiments performed at PSI.⁴ The target is designed to be service and user friendly. The sample holding device can be removed or inserted into the cryostat at 4 K. PSI experience is that the target can be installed in the time period of one day. The PSI design is ideal for experiments that can utilize small (1 cm $\times$ 1 cm) beam spots. Several years ago we decided to make a copy of the PSI refrigerator and build our own compact dynamically polarized nuclear target.

Schematic diagrams of the cryostat, the ^3He evaporation unit, and the ^3He - ^4He dilution refrigerator unit are shown in Figs. 1-3. PSI provided us with a complete set of engineering drawings for the system. S. Penttilä (LAMPF) is an important collaborator on this project.

The cryostat construction is complete and the initial cooldown was successful. Construction of the ^3He evaporation unit is also complete. All components for the 70 GHz microwave system required for DNP (at a magnetic field of 2.5 T) have been acquired. We have also acquired most of the components required for the NMR system as well as the CAMAC-controlled NMR system. The 2.5 T superconducting split-coil magnet has been integrated into the refrigeration system and will be tested during the next cooldown. The ^3He recirculation-storage-system

is finished, apart from the assembly of the main blower package. Also, construction of the ^4He transfer system has been completed.

Shop work on this project has competed with work on other higher priority projects such as (1) the EXP1079 apparatus (see section 2.3), (2) the E871 muon hodoscope (see section 4.3), and (3) STAR SVT and TPC construction projects (see section 5). About 2 man-years of shop time has been invested in the polarized target project.

Figs. 4-7 are photographs of the cryostat, the ^3He evaporation insert, the superconducting split coil magnet, and parts of the ^3He recirculation system.

The present plan is to move the equipment to the Triangle Universities Nuclear Laboratory (TUNL) in January 1994 and collaborate with D. Haase (NCSU), C. Gould (NCSU), R. Roberson (Duke) and W. Tornow (Duke) in a program to instrument the equipment and use it for $\vec{n} + \vec{p}$ transmission experiments. Total cross sections will be measured for energies from a few MeV to about 10 MeV. The goal of the $\vec{n} + ^1\vec{\text{H}}$ experiments is to provide precision polarized total cross section data which can be used to better determine the $J = 1$ NN mixing angle at low energies, thereby making it possible to set important, new constraints on the NN tensor interaction.⁵ Another possible use of our target at low energies with heavier polarized nuclei involves tests of fundamental symmetries.

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Figure Captions

Figure 1: Schematic of PSI standard cryostat with central tube for ^3He evaporation insert (Fig. 2) or dilution unit (Fig. 3).

Figure 2: Schematic of PSI ^3He evaporation unit and sample holding device.

Figure 3: Schematic of PSI ^3He - ^4He dilution refrigerator unit with corresponding sample holding device.

Figure 4: Photograph of the cryostat of the evaporation refrigerator.

Figure 5: Photograph of the ^3He evaporation unit.

Figure 6: Photograph of the superconducting split coil magnet.

Figure 7: Photograph of components of the ^3He recirculation system.

Figure 3

Figure 2

Figure 1

Figure 4

Figure 5

Figure

4 Experiments at Brookhaven National Laboratory

4.1 AGS E791: Search for $K_L^0 \rightarrow \mu e$

(G. Hoffmann; UCI; UCLA; LANL; Stanford; Temple; Texas William and Mary; R. Cousins, W. Molzon, spokesmen)

Summary: A search was made for the forbidden decay $K_L^0 \rightarrow \mu e$ with experimental sensitivity much improved over previous efforts. The search has yielded no events. The 90% confidence level limit on the branching ratio is $B(K_L^0 \rightarrow \mu^\pm e^\mp) < 3.9 \times 10^{-11}$. When this data set is combined with earlier data the upper limit is 3.3×10^{-11} .

The decay $K_L^0 \rightarrow \mu^\pm e^\mp$ is forbidden by conservation of the separate additive quantum numbers for electron- and muon-type leptons. Unlike the conservation law for electric charge, these laws are not a consequence of a gauge theory of particle interactions. The Standard Model contains no mechanism violating these laws; hence an observation of this decay would be evidence of new interactions. For example, the decay could occur through the production and decay of a virtual particle X^0 which couples to the s and d quarks at one vertex and to muons and electrons at the other. An observation of this decay with a branching ratio of 10^{-10} would imply a mass for X^0 of $\sim 100 \text{ TeV}/c^2$, if the coupling strength is the standard electroweak coupling g . Nearly all extensions to the Standard Model allow for muon and electron number violation,¹ although usually at a level below the sensitivity of current experiments.

The experiment was performed at the B-5 beamline of the Alternating Gradient Synchrotron (AGS) at BNL. Data were collected during two running periods in 1989 and 1990 of approximately 15 and 12 weeks duration. The final results of E791 are reported in Ref. (2) and are discussed here. The present experiment achieved a sensitivity greater than previously attained.³⁻⁷

An average of 4.5×10^{12} protons per spill at 24 GeV/c were incident on a 1.3-interaction-length Cu target. A neutral beam subtending a solid angle of 4.1 (hor.) $\times$ 15.0 (vert.) mrad² (FWHM) was produced at a mean angle of 2.75° to the proton beam. Following the beam-defining elements, an 8.5 m long vessel evacuated to 0.020 Torr served as a fiducial decay region. A three-piece decay region end window assembly used during 1989 was replaced by a single-round-kevlar/mylar window for the 1990 run. Fig. 1 shows a plan view of the E791 spectrometer and neutral beamline.^{6,8,9}

The spectrometer consisted of five pairs of drift chambers (DC1-5) and two

analyzing magnets with transverse momentum impulses of 300 MeV/c and 318 MeV/c of opposite sign. The chambers contained two x- and two y-measuring planes, each with 120 μm single-wire resolution. For the 1990 run the two most upstream chambers were replaced with larger modules placed closer to the neutral beam, resulting in a 30% increase in acceptance. Downstream of the drift chambers were two pairs of trigger scintillation counters (TSC's) and particle identification detectors (PID's). Electrons were identified with a threshold gas Cherenkov counter (CER) and a lead-glass array (PBG), both with time and pulse height information. The PBG array was composed of two layers, a converter array (3.3 r.l.) and an absorber array (10.5 r.l.). Muons were identified with a scintillator hodoscope (MHO) and a range finder (MRG)¹⁰ located downstream of 0.91 m of iron. The latter contained drift tube detectors inserted in marble and aluminum absorber at intervals corresponding to 10% increments of range.

A Level 0 (L0) hardware trigger was defined by an overlap coincidence of the four TSC's. A 'minimum bias' signal was formed from a coincidence of the L0 trigger with the 3 most upstream drift chambers on each side of the spectrometer. The Level 1 (L1) trigger selected minimum bias events prescaled by 2000 and dilepton events defined by a coincidence of the minimum bias signal and a MHO or CER signal on each side of the apparatus. Events satisfying the L1 trigger were processed in one of eight 3081/E computers.¹¹

A Level 2 trigger was designed but never used in either data taking period. The Level 3 (L3) trigger algorithm used hit information from DC1-3 and a lookup table of field integrals for the first magnet to calculate a 2-body mass (M_{12}) and collinearity angle (θ_K) defined as the difference between the kaon direction calculated from the target and vertex positions and the reconstructed 2-body momentum direction. Values of M_{12} for each combination of lepton masses consistent with the L1 trigger were calculated. Di-lepton triggers were required to have $\theta_K^2 < 100 \text{ mrad}^2$, $M_{12} > 460 \text{ MeV}/c^2$ and, during 1989 only, $M_{12} < 550 \text{ MeV}/c^2$. There were no L3 requirements on the minimum bias triggers. Events passing the L3 selection criteria were written to magnetic tape. The efficiency of this algorithm was measured using minimum bias events, subject to the event quality and kinematic cuts described below, to be 66% ('89) and 91% ('90). The improved efficiency in 1990 was achieved with modifications of the algorithm to find events with missing hits and events contaminated with extra hits in the chambers more effectively.

Offline, events were reconstructed with a pattern recognition algorithm which used the hit information from all drift chambers to find tracks that originated from a common vertex and traversed the full spectrometer. For each view (x and y) of each track, at least 8 of 10 expected drift chamber signals were required. The invariant mass and collinearity were recalculated and the transverse momentum (P_T), defined to be the product of the two body momentum with the collinearity angle, was calculated. Events with $M_{12} > 470 \text{ MeV}/c^2$ and either $\theta_K^2 < 10 \text{ mrad}^2$ or $P_T^2 < 800 (\text{MeV}/c)^2$ were selected. For the 1989 run it was also required that $M_{12} < 530 \text{ MeV}/c^2$. Events satisfying these criteria were then fit using a full

magnetic field map to determine more accurately their kinematics.

Fitted tracks were projected to the PID detectors and measured responses compared to those expected. Tracks were identified as electrons if they had an associated CER hit within 4 ns of the event time, if the ratio of energy in the PBG to the particle momentum was greater than 0.65, and if they deposited sufficient energy in the converter blocks.¹² The efficiencies of the cuts on the CER and PBG were measured to be 0.908 ± 0.001 and 0.958 ± 0.001 using electrons from $K_L^0 \rightarrow \pi e \nu$ (K_{e3}) decays obtained from the minimum bias data sample.

Muons were identified by requiring that the positions of struck MHO counters and their times agree with expected values, that a minimum fraction of expected MRG hits were found by a tracking algorithm, and that the measured range in the MRG exceeded 90% of that expected from the particle's momentum.^{8,9,12,13} The efficiencies of the cuts on the MHO and MRG were measured to be 0.969 ± 0.001 and 0.975 ± 0.001 using muons from $K_L^0 \rightarrow \pi \mu \nu$ ($K_{\mu 3}$) decays obtained from the minimum bias data sample.

The primary source of background in the search for $K_L^0 \rightarrow \mu^\pm e^\mp$ is K_{e3} decays. One class of background consists of the pion being misidentified as or decaying to a muon. In the absence of measurement errors, this class of events has a μe mass distribution with a kinematic endpoint $8.4 \text{ MeV}/c^2$ below the kaon mass. Excellent kinematic resolution is required to reject such events. A particularly serious source of background was found to come from such events, with a decayed pion, where in addition a mistake was made in the kinematic reconstruction of the event. In this case the reconstructed mass can be equal to or larger than M_K . A second class of background arises from the misidentification of the pion as an electron and the misidentification of the electron as a muon. These events can also have a reconstructed μe mass greater than M_K . Rejection of these events requires excellent particle identification.

The analysis proceeded by studying background events with $M_{\mu e}$ within 5 MeV/c^2 of M_K and with $144 < P_T^2 \leq 800 \text{ (MeV}/c)^2$ and choosing cuts to reduce this background. The mass interval was chosen to be approximately 3 times the expected resolution in $M_{\mu e}$ ($1.74 \text{ MeV}/c^2$), based on the measured resolution in $M_{\pi\pi}$ ($1.40 \text{ MeV}/c^2$) and a Monte Carlo calculation of the ratio of the resolution for $M_{\mu e}$ ($1.57 \text{ MeV}/c^2$) to that for $M_{\pi\pi}$ ($1.26 \text{ MeV}/c^2$). The P_T^2 cut at 144 $(\text{MeV}/c)^2$ was chosen in a similar fashion. These events were studied to understand the classes of events that were the most troublesome and to devise selection criteria to eliminate them. Only after the final event selection criteria had been chosen, were events inside the signal region $P_T^2 \leq 144 \text{ (MeV}/c)^2$ analyzed.

Events were required to have a vertex at least 9.75 m from the target and within a region defined by the beam divergence. Events with charged particle trajectories which projected to large amounts of material (e.g. vacuum flange, magnet coils) or which missed the PID detectors were eliminated. The momenta of charged particles were required to be above $1.5 \text{ GeV}/c$ and below $12.0 \text{ GeV}/c$.

The ratio of the lepton momenta was required to be less than five to reduce the

number of K_{e3} events with a decaying pion that are reconstructed with a μe mass near the kinematic endpoint. Most events with pion decays within the tracking spectrometer were eliminated by requirements on the track and vertex quality, and on the consistency of the momenta as measured by the front and back halves of the spectrometer.

Mistakes in the kinematic reconstruction were reduced by removing events with missing hits where the fitting routine chose an ambiguity resolution that had a low probability of being correct, for example, if the side of the wire opposite to a 'dead' wire was chosen. Further cuts in the 1990 sample included removing events with two or more misses in the x-view of any track, and removing events which had both a high momentum track ($P > 7$ GeV/c) and an x-view miss. Events with large P_T in the putative kaon decay plane were found more often to have high values of $M_{\mu e}$; hence the accepted region in P_T^2 was further reduced by requiring P_T in the decay plane to be less than 7 MeV/c.

After final determination of the selection criteria, events in the signal region were analyzed and the cuts applied. No events were found. Fig. 2 is a plot of P_T^2 vs. $M_{\mu e}$ for our final sample of $K_L^0 \rightarrow \mu^\pm e^\mp$ candidates from both data sets.

The total K_L^0 flux is obtained by counting the $K_L^0 \rightarrow \pi^+\pi^-$ decays in the prescaled minimum bias data sample. The distribution of the two body invariant mass, assuming pion masses for the charged particles ($M_{\pi\pi}$), is shown for this sample in Fig. 3. Superimposed is a Monte Carlo simulation of the $M_{\pi\pi}$ distribution for semileptonic decays of K_L^0 . This distribution is normalized to the data outside the K_L^0 mass peak and then subtracted to obtain a $\pi\pi$ count. Both distributions have been corrected to account for the K_S^0 contamination of the $\pi\pi$ sample. The value of this correction has been calculated to be $\xi_{K_S} = 0.987 \pm 0.001$ ('89) and 0.992 ± 0.001 ('90). The resulting number of $K_L^0 \rightarrow \pi^+\pi^-$ events is $N_{\pi\pi} = 15033 \pm 151$ ('89) and 29430 ± 217 ('90).

Since no events consistent with the decay $K_L^0 \rightarrow \mu^\pm e^\mp$ were observed we compute a 90% confidence level limit on the branching ratio from

$$B(K_L^0 \rightarrow \mu^\pm e^\mp) < 2.3 \times \alpha \times \frac{B(K_L^0 \rightarrow \pi^+\pi^-)}{R \times N_{\pi\pi}} \times \frac{A_{\pi\pi}}{A_{\mu e}} \times \frac{\epsilon_{\pi\pi}}{\epsilon_{\mu e}}. \quad (4.1)$$

The factor $\alpha = 1 + 1.15\sigma_r^2$ incorporates the effects of the fractional systematic uncertainty, σ_r (Ref. 14). Including all the uncertainties listed below and the uncertainty on the $\pi\pi$ counting, we estimate σ_r to be less than 5%, resulting in a negligible effect on the upper limit quoted. The branching ratio $B(K_L^0 \rightarrow \pi^+\pi^-) = (2.03 \pm 0.04) \times 10^{-3}$ (Ref. 15). The acceptance ratio determined from a Monte Carlo simulation of the detector is $A_{\pi\pi}/A_{\mu e} = 1.47 \pm 0.01$ ('89) and 1.42 ± 0.01 ('90). A small correction has been applied to this ratio to account for the difference in measured and calculated mass resolution. The total $\pi\pi$ prescale factor, R , including both the L1 prescale and an offline prescale, is 6000 ('89) and 4000 ('90).

We have broken $(\epsilon_{\pi\pi}/\epsilon_{\mu e})$ down into four components:

$$\frac{\epsilon_{\pi\pi}}{\epsilon_{\mu e}} = \left(\frac{\epsilon_{\pi\pi}}{\epsilon_{\mu e}}\right)^{L3} \times \epsilon_{\pi\pi}^{\text{int}} \times \frac{1}{\epsilon_{\mu e}^{\text{PID}}} \times \frac{1}{\epsilon_{\mu e}^{\text{L1}}}. \quad (4.2)$$

The first factor, the L3 correction, has been measured using the minimum bias sample to be $(\epsilon_{\pi\pi}/\epsilon_{\mu e})^{L3} = 1.001 \pm 0.003$ ('89) and 1.002 ± 0.001 ('90). The correction for pion loss due to interactions in the spectrometer has been estimated, from data with the downstream trigger scintillators removed from the trigger, to be $\epsilon_{\pi\pi}^{\text{int}} = 0.954 \pm 0.004$. The efficiency for identifying the μe pair from $K_L^0 \rightarrow \mu^\pm e^\mp$ has been measured from K_{e3} and $K_{\mu 3}$ decays in our minimum bias sample to be $\epsilon_{\mu e}^{\text{PID}} = 0.790 \pm 0.006$ ('89) and 0.814 ± 0.005 ('90). These numbers are integrations of the lepton detection efficiencies over kinematic distributions expected for $K_L^0 \rightarrow \mu^\pm e^\mp$. Finally the L1 lepton trigger efficiency has been measured to be $\epsilon_{\mu e}^{\text{L1}} = 0.988 \pm 0.003$ ('89) and 0.990 ± 0.002 ('90). This factor is the efficiency of the L1 trigger being satisfied, given that the offline PID criteria have been satisfied.

The resulting 90% confidence limit on the branching ratio is $B(K_L^0 \rightarrow \mu^\pm e^\mp) < 9.3 \times 10^{-11}$ ('89) and $< 6.7 \times 10^{-11}$ ('90). The combined result from both data sets is $B(K_L^0 \rightarrow \mu^\pm e^\mp) < 3.9 \times 10^{-11}$ at 90% CL. Combined with our earlier result using a similar apparatus,⁶ the limit is $B(K_L^0 \rightarrow \mu^\pm e^\mp) < 3.3 \times 10^{-11}$. We have found no evidence that the additive quantum numbers associated with muon and electron-type leptons are not conserved and have further restricted the effective coupling strengths of new interactions which allow for violation of these conservation laws.

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Figure Captions

Figure 1: The E791 beam line and detector.

Figure 2: Plot of P_T^2 vs $M_{\mu e}$. Plus signs are 1989 data and circles are 1990 data.

Figure 3: Distribution in $M_{\pi\pi}$ for minimum bias data (histogram) and Monte Carlo semileptonic background (circles).

Figure 1

Figure 2

Figure 3

4.2 AGS E791: Search for $K_L^0 \rightarrow e^+e^-$

(G. Hoffmann, J. McDonough; UCI; UCLA; LANL; Stanford; Temple; Texas; William and Mary; R. Cousins, W. Molzon, spokesmen)

Summary: A search was made for the rare decay $K_L^0 \rightarrow e^+e^-$; no candidates were observed. We determined the sensitivity from the detected number of CP -violating $K_L^0 \rightarrow \pi^+\pi^-$ decays and place a 90% confidence level upper limit on the branching ratio of $B(K_L^0 \rightarrow e^+e^-, |M_K - M_{ee}| < 6 \text{ MeV}/c^2) \leq 4.1 \times 10^{-11}$. This result is a significant improvement over previous measurements, although still above the Standard Model prediction of 3×10^{-12} .

The decay $K_L^0 \rightarrow e^+e^-$ is the helicity-suppressed counterpart of the effective flavor-changing neutral current process $K_L^0 \rightarrow \mu^+\mu^-$ which has played an important role in the development of the Standard Model. Recent measurements of the $K_L^0 \rightarrow \mu^+\mu^-$ branching ratio,¹⁻³ near the QED lower limit obtained from the contribution of the on-shell part of the two-photon intermediate state⁴ (often called the unitarity bound), imply that this decay is dominated by Standard Model processes. A search for the decay $K_L^0 \rightarrow e^+e^-$ at a sensitivity approaching the Standard Model level of 3×10^{-12} is then sensitive to new contributions which may not be suppressed by the V-A structure of the weak interaction. This work⁵ involves a search for the decay $K_L^0 \rightarrow e^+e^-$; a significantly improved upper limit on the branching ratio for this process^{6,7} was obtained. The limit is still roughly an order of magnitude above the Standard Model prediction.

Refer to section 4.1 (Ref. 8) for a detailed description of the E791 set up.

Trigger decisions were made at multiple levels. The first two levels (referred to as L0 and L1) were made in hardware. The third level (L3) was based on a software algorithm running in a farm of 3081/E computers.⁹ (A Level 2 trigger was designed but never used in either running period.) The L0 trigger was defined as an overlap coincidence of the four TSC's in which the hits in the vertical and horizontal views were required to be consistent in position and time. A 'minimum bias' signal was formed from a coincidence of the L0 trigger signal with signals from the 3 most upstream drift chambers on each side of the spectrometer. The L1 trigger selected ee candidate events, defined by a coincidence of the minimum bias signal with a CER signal on each side of the apparatus. It also included minimum bias events prescaled by 2000, from which the sample of $K_L^0 \rightarrow \pi^+\pi^-$ events used to calculate the sensitivity of the experiment was selected.

The L3 trigger decision was based on the 2-body mass (M_{ee}) and the collinearity angle (θ_K), defined as the difference between the kaon direction obtained from the target and vertex positions and the reconstructed 2-body momentum direction. Electron pair triggers were required to have $\theta_K^2 < 100 \text{ mrad}^2$, $M_{ee} > 460 \text{ MeV}/c^2$ and, in 1989 only, $M_{ee} < 550 \text{ MeV}/c^2$. The efficiency of this algorithm

was measured, using minimum bias events passing the event quality and kinematic cuts described below, to be 66% (1989) and 91% (1990). The improved efficiency in 1990 was achieved with modifications to the code to find events with missing hits and events contaminated with extra hits in the chambers more effectively. Also, an inherent bias against like-charge events in the 1989 L3 algorithm was removed from the 1990 L3 algorithm. These events were important in understanding backgrounds to the $K_L^0 \rightarrow e^+e^-$ search.

Events with at least two tracks traversing the full spectrometer and originating from a common vertex were reconstructed and further analyzed offline. The invariant mass and collinearity were recalculated and the transverse momentum (p_T), defined to be the product of the two-body momentum with the collinearity angle, was calculated. Events with $M_{ee} > 470 \text{ MeV}/c^2$ and either $\theta_K^2 < 10 \text{ mrad}^2$ or $p_T^2 < 800 (\text{MeV}/c)^2$ were selected. In the analysis of the 1989 data it was also required that $M_{ee} < 530 \text{ MeV}/c^2$. Events satisfying these criteria were then fit using a full magnetic field map to determine their kinematics more accurately. The minimum bias sample was further prescaled offline by a factor of 3 (2) in 1989 (1990). Thus the overall prescale of the $K_L^0 \rightarrow \pi^+\pi^-$ normalization sample was 6000 (4000).

As in the search for the decay $K_L^0 \rightarrow \mu^\pm e^\mp$, selection criteria were devised without studying events in the kinematic region in which signal events are expected.⁸ Specifically, events in the region defined by $|M_{ee} - M_K| < 10 \text{ MeV}/c^2$ and $\theta_K^2 < 2 \text{ mrad}^2$ were excluded from analysis until the selection criteria had been chosen. All selection criteria except PID were applied to both the $K_L^0 \rightarrow e^+e^-$ and the normalization data samples.

Candidate events were required to have a vertex at least 9.75 m from the target and within a region defined by the beam divergence. Events with charged particle trajectories which projected to the vacuum flanges or other thick materials were eliminated. The charged particles were required to have momenta above 1.5 GeV/c and below 12.0 GeV/c. The reconstructed kaon momentum was required to be below 20 GeV/c. (The mean kaon momentum of detected $K_L^0 \rightarrow \pi^+\pi^-$ events was 8.0 GeV/c.) Track and vertex quality were assured by cutting on χ^2 's calculated during the fitting procedure. The asymmetry in the two charged particle momenta, $|p_1 - p_2|/|p_1 + p_2|$, was required to be less than 0.67 in order to remove $\Lambda^0 \rightarrow p^+\pi^-$ events from the $K_L^0 \rightarrow \pi^+\pi^-$ normalization sample.

The signals in those elements of the CER and PBG detectors to which fitted tracks projected were compared to those expected for different particle types. To be identified as electrons, particles were required to have an associated CER hit within 4 ns of the event time, where the RMS timing resolution was measured to be 0.95 ns for electrons from $K_L^0 \rightarrow \pi^\pm e^\mp \nu$ decays. In addition, these tracks were required to have an appropriate signal in the PBG array. Specifically, particles identified as electrons had to lie above and to the right of the contour indicated in Fig. 1. That contour was determined empirically from the study of $K_L^0 \rightarrow \pi^\pm e^\mp \nu$ events so as to obtain optimum pion rejection consistent with high electron identification efficiency.

Events with M_{ee} above 470 MeV/c² still remained after applying the above criteria. Potential sources of high mass e^+e^- pairs are K_L^0 decays into $e^+e^-e^+e^-$, $e^+e^-\gamma$, or $\gamma\gamma$, the latter two with photon conversions in the vacuum window or upstream drift chambers. The background from these sources was studied by Monte Carlo techniques and by looking in the data for events either with extra tracks in the two upstream drift chamber planes or with like-charge ee pairs. Background from $K_L^0 \rightarrow \pi^\pm e^\mp \nu$ decays is highly suppressed since it requires a pion to be misidentified as an electron and is kinematically restricted to values of M_{ee} below 478 MeV/c² in the absence of measurement errors.

In order to test our understanding of the sources of high-mass ee pairs of both like- and unlike- charge, we focussed our attention on the 1990 data, since the 1989 L3 code had an unmeasurable bias against like-charge events. Fig. 2 is a scatter plot of θ_K^2 vs. M_{ee} for the 1990 data. Events with one particle momentum above pion CER threshold and $M_{ee} < 478$ MeV/c² have been eliminated for clarity; these events are K_{e3} in which the pion is misidentified as an electron in the PBG. Real $K_L^0 \rightarrow e^+e^-$ events would be concentrated on the plot around $\theta_K = 0$ and $M_{ee} = M_K = 497.67$ MeV/c².

We have estimated the number of events expected in Fig. 2 from $K_L^0 \rightarrow e^+e^-\gamma$ and $K_L^0 \rightarrow e^+e^-e^+e^-$ by the Monte Carlo technique.¹⁰ The $K_L^0 \rightarrow e^+e^-\gamma$ Monte Carlo used the Kroll-Wada differential decay spectrum,¹¹ modified by inclusion of a vector-vector term in the $K_L^0 \rightarrow \gamma\gamma^*$ form factor.¹²⁻¹⁴ If the real photon in the $K_L^0 \rightarrow e^+e^-\gamma$ process is sufficiently soft, the event can take on an e^+e^- invariant mass arbitrarily close to M_K . Assuming a $K_L^0 \rightarrow e^+e^-\gamma$ branching ratio of 9.1×10^{-6} (Refs. 13 and 14), we predict 2 ± 1 events from $K_L^0 \rightarrow e^+e^-\gamma$ within the phase space of Fig. 2. The uncertainty in this prediction is dominated by the uncertainty in the $K_L^0 \rightarrow \gamma\gamma^*$ form factor.

The Monte Carlo calculation of the $K_L^0 \rightarrow e^+e^-e^+e^-$ events in Fig. 2 was based on the differential decay spectrum of Miyazaki and Takasugi,¹⁵ for double internal conversions. A flat $K_L^0 \rightarrow \gamma^*\gamma^*$ form factor was assumed. This is a reasonably accurate approximation since the largest contribution to the events in Fig. 2 arises when two low mass intermediate photons convert asymmetrically. (The effect of the form factor is small when the intermediate photons have low mass.)

Using a branching ratio for this decay of 4×10^{-8} (Refs. 16-18) we predict 7 ± 1 events in the full region of Fig. 2. The uncertainty in this prediction is primarily statistical. Half of the 7 events are expected to be like-charge (5 are observed) and 2 of these 7 will contain one or two extra tracks in the upstream drift chambers (3 are seen).

Finally, approximately 1 event is expected in Fig. 2 from the photons from $K_L^0 \rightarrow e^+e^-\gamma$ and $K_L^0 \rightarrow \gamma\gamma$ decays converting in the vacuum window or first drift chamber. Thus the total predicted level of events in Fig. 2 from the decays $K_L^0 \rightarrow \gamma\gamma$, $K_L^0 \rightarrow e^+e^-\gamma$ and $K_L^0 \rightarrow e^+e^-e^+e^-$ (10 ± 2 events) agrees well with that observed (11 are seen).

Approximately half of the events in Fig. 2 are eliminated by requiring the events

to have oppositely charged particles and requiring that no extra track project to within one centimeter of the event vertex. The minimum criteria for an extra track is that it have hits in both views of the first two drift chamber planes. The loss of real events due to the extra track cut was estimated to be 0.8% for both $K_L^0 \rightarrow e^+e^-$ and $K_L^0 \rightarrow \pi^+\pi^-$ events, based on measurements using $K_L^0 \rightarrow \pi^\pm e^\mp \nu$ events.

Fig. 3 is a scatter plot of θ_K^2 vs. M_{ee} for events from both data sets which pass all selection criteria described above. Events in this plot are classified as $K_L^0 \rightarrow e^+e^-$ if they have $\theta_K^2 < 2.0 \text{ mrad}^2$ and a mass within $6.0 \text{ MeV}/c^2$ of the K_L^0 mass. The values of the cuts on θ_K^2 and M_{ee} were chosen to minimize the probability of including background events in the signal region while maintaining good acceptance. The value chosen for the mass cut corresponds to approximately 3σ in the resolution. The collinearity cut was left at 2 mrad^2 , as tightening this cut was expected to have little effect on backgrounds. Monte Carlo calculations of the background sources described above predict that we should see fewer than 0.15 events in the signal region of Fig. 3. No events satisfy these criteria.

In the decay $K_L^0 \rightarrow e^+e^-$, the invariant mass of the e^+e^- pair can be reduced if a photon is radiated via the inner bremsstrahlung (IB) process. Therefore, the signal region is restricted to events in which the energy of the radiated photon is less than 6 MeV. Events with radiated photons of greater energy account for 17% of the total IB-corrected $K_L^0 \rightarrow e^+e^-$ rate.¹⁹ We do not apply a correction to account for this effective loss in acceptance. A negligible fraction of the IB-corrected rate fails the collinearity cut exclusively.

Based on our observation of no signal events, we determine a 90% C.L. upper limit on the $K_L^0 \rightarrow e^+e^-$ branching ratio by evaluation of the following expression:

$$B(K_L^0 \rightarrow e^+e^-) \leq 2.3 \times \frac{B(K_L^0 \rightarrow \pi^+\pi^-)}{R \times N_{\pi\pi}} \times \frac{A_{\pi\pi}}{A_{ee}} \times \frac{\epsilon_{\pi\pi}}{\epsilon_{ee}} \times \frac{\epsilon_{\pi\pi}^{L3}}{\epsilon_{ee}^{L3}}. \quad (4.3)$$

$N_{\pi\pi}$ is the number of detected $K_L^0 \rightarrow \pi^+\pi^-$ events, after the prescale factor R . The branching ratio $B(K_L^0 \rightarrow \pi^+\pi^-) = (2.03 \pm 0.04) \times 10^{-3}$ (Ref. 20). The ratio of $K_L^0 \rightarrow \pi^+\pi^-$ to $K_L^0 \rightarrow e^+e^-$ acceptances $A_{\pi\pi}/A_{ee}$ was determined from a Monte Carlo simulation of the detector. The correction for pion loss due to interactions in the spectrometer and TSC is $\epsilon_{\pi\pi}$; this was obtained by analysis of specially triggered data. The efficiency for identifying electrons has been measured using K_{e3} decays in our minimum bias sample. From this the $K_L^0 \rightarrow e^+e^-$ particle identification efficiency ϵ_{ee} was derived. Finally, $\epsilon_{\pi\pi}^{L3}/\epsilon_{ee}^{L3}$ is the ratio of efficiencies of the L3 trigger for the $\pi^+\pi^-$ and e^+e^- modes. The values of these parameters are given in Table II for the two data sets. The uncertainty in the relative acceptance and efficiencies for the $K_L^0 \rightarrow \pi^+\pi^-$ and $K_L^0 \rightarrow e^+e^-$ decay modes is less than 5%; this has a negligible effect on the limit quoted.^{8,21}

We place 90% C.L. upper limits on the branching ratio for the process $K_L^0 \rightarrow e^+e^-$ of $B(K_L^0 \rightarrow e^+e^-) < 11.9 \times 10^{-11}$ (1989), and $B(K_L^0 \rightarrow e^+e^-) < 7.8 \times 10^{-11}$ (1990). These limits include events with less than 6 MeV of radiated energy. These

new results, combined with our previous limit,⁶ give $B(K_L^0 \rightarrow e^+e^-, |M_K - M_{ee}| < 6 \text{ MeV}/c^2) < 4.1 \times 10^{-11}$ at 90% C.L. This is consistent with the predictions of the Standard Model.

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Figure Captions:

Figure 1: A scatter plot of the fraction of energy deposited in the converter layer of the PBG (E_C/E_{TOT}) versus the ratio of the deposited energy to measured momentum (E_{TOT}/P), for particles from minimum bias data. Particles in the region above and to the right of the indicated contour are identified as electrons in the PBG.

Figure 2: Scatter plot of θ_K^2 vs. M_{ee} for events from the 1990 data set which satisfy all selection criteria except those on θ_K^2 and M_{ee} . Events identified as originating from $K_L^0 \rightarrow \pi^\pm e^\mp \nu$ have been removed. Like-charge events (identified with o's), and events with one or more extra tracks detected in the upstream two drift chamber planes (identified with + 's) have been restored to the plot.

Figure 3: Scatter plot of θ_K^2 vs. M_{ee} for events from the combined 1989 and 1990 data sets which satisfy all selection criteria except those on θ_K^2 and M_{ee} . Events identified as originating from $K_L^0 \rightarrow \pi^\pm e^\mp \nu$ are included in this plot.

Table II: Factors entering into the calculation of the $K_L^0 \rightarrow e^+e^-$ limit for the 1989 and 1990 data sets.

Variable	1989	1990
$N_{\pi\pi}$	$15,118 \pm 151$	$31,354 \pm 217$
R	6000	4000
$A_{\pi\pi}/A_{ee}$	1.78 ± 0.01	1.69 ± 0.01
$\epsilon_{\pi\pi}$	0.954 ± 0.004	0.954 ± 0.004
ϵ_{ee}	0.733 ± 0.009	0.775 ± 0.007
$\epsilon_{\pi\pi}^{L3}/\epsilon_{ee}^{L3}$	1.00 ± 0.01	1.01 ± 0.01

Figure 1

Figure 2

Figure 3

4.3 AGS E871: New Search For Very Rare K_L Decays

(G. W. Hoffmann, J. McDonough, S. Worm;
UCI; Stanford; Temple; Texas; William and Mary;
W. R. Molzon, J. L. Ritchie, S. G. Wojcicki, spokesmen)

Summary: This experiment is a new search for the decays $K_L \rightarrow \mu e$ and $K_L \rightarrow ee$. A single event sensitivity for $K_L \rightarrow \mu e$ below 10^{-12} will be reached and if no events are observed, an upper limit of about 2×10^{-12} will be set. A few $K_L \rightarrow ee$ events should be observed, if this decay occurs at the rate predicted by the Standard Model, or more if new mechanisms contribute. About 10^4 $K_L \rightarrow \mu\mu$ decays will also be observed, thus improving considerably the accuracy of this branching ratio (BR). The principal improvements over the previous experiment (E791) are: increased beam (about a factor of 4) made possible by the Booster upgrade at the AGS, increased acceptance (more than a factor of 2), and improved efficiencies (more than a factor of 2). The most critical feature of the new experiment, the beam-plug, was extensively tested during the past two years. The results from these tests confirm the feasibility of the experiment and provide important data on the detector rates in the new experiment. Besides the beam plug, we have also designed, constructed, and commissioned, an instrumented muon filter for the new experiment; its purpose is to limit trigger rates and to reduce backgrounds from $\pi - \mu$ misidentification. We are responsible for the new trigger logic for this experiment. An extensive engineering run occurred in Summer 1993.

Physics Motivation

The Standard Model is considered successful, but it is incomplete: (1) there are nineteen free parameters in the theory, (2) there is no explanation of why quarks and leptons appear in three generations, or why there should not be more, (3) there is no explanation of how 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, and (5) there is no unification of the strong and electroweak interactions (and gravity is not in the picture). A number of proposed extensions of the Standard Model have been suggested including supersymmetry,¹ technicolor,² right-left symmetry,³ horizontal gauge symmetry,^{4,5} compositeness,⁶ and some superstring inspired models.⁷ Typically, conservation of lepton number is violated in these extensions.

It is appropriate to consider alternative searches for lepton number violation and related physics. These include: (1) $\mu \rightarrow e\gamma$, (2) $\mu \rightarrow eee$, (3) $\mu A \rightarrow eA$ (muon conversion on a nucleus), and (4) Δm_K (the K_L - K_S mass difference). Processes such as $\mu \rightarrow e\gamma$ and $\mu \rightarrow eee$ 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. The process $\mu A \rightarrow e A$ also does not involve a generation-change in the quark sector. The small value of Δm_K (3.5×10^{-15} GeV) provides a serious constraint for 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 . Also, leptoquark exchange is not constrained at all by Δm_K .

To quantify this discussion we use the model of Cahn and Harari⁵ for generation-changing gauge bosons to illustrate the mass scales probed by each of these processes. Table III lists the best present limit for each process and the mass scale probed. The limit given for $K_L \rightarrow \mu e$ is the lowest limit yet reported from E791 (Ref. 8), but is not the final E791 result from the full (three years) data set. The bottom row shows the mass reach of the new experiment. The mixing angles (β) characterize the generation mixing in the model and are unconstrained. If generation number is approximately conserved, then the mixing angles would be small. The mixing angles do not appear in the expressions for the mass reach for the two kaon decays. It is easy to conclude from these considerations that a search for $K_L \rightarrow \mu e$ approaching the 10^{-12} level is important and that the prospects for observing $K_L \rightarrow \mu e$ in this new search are not ruled out by previous limits.

Process and Present Value	Mass Reach
Δm_K (3.5×10^{-15} GeV)	400 TeV $\sin \beta_D$
$Br(\mu \rightarrow e\gamma) < 1.7 \times 10^{-11}$	20 TeV $ \sin \beta_L \cos \beta_L ^{1/2}$
$Br(\mu \rightarrow eee) < 1 \times 10^{-12}$	80 TeV $ \sin \beta_L \cos \beta_L ^{1/2}$
$\Gamma(\mu A \rightarrow e A) / \Gamma(\mu A \rightarrow \nu A) < 4.6 \times 10^{-12}$	190 TeV $ \sin \beta_{LU} - \sin \beta_{LD} ^{1/2}$
$Br(K^+ \rightarrow \pi^+ e^- \mu^+) < 2.1 \times 10^{-10}$	40 TeV
$Br(K_L \rightarrow \mu e) < 3.3 \times 10^{-11}$	90 TeV
$Br(K_L \rightarrow \mu e) < 2.0 \times 10^{-12}$ (this experiment)	180 TeV

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

Finally, while the theoretical considerations are encouraging, the ultimate justification for an improved $K_L \rightarrow \mu e$ search is simply to test the rule of separate lepton number conservation to the highest precision possible with existing accelerators and detectors.

The allowed, but very rare decay, $K_L \rightarrow ee$, is expected⁹ to occur at a branching ratio of about 3×10^{-12} ; the present limit from E791 is $< 4.1 \times 10^{-11}$. The range between these values is a window for observing a possible new flavor changing neutral current interaction.

Results of E791

The analysis of the final data set, taken in 1990, is complete. The $K_L \rightarrow \mu e$ result has been published,¹⁰ and the $K_L \rightarrow ee$ result has been accepted for

publication by Physical Review Letters. The $K_L \rightarrow \mu\mu$ result will be submitted soon. The most precise published¹¹ branching ratio measurement of $K_L \rightarrow \mu\mu$ is from the E791 1989 data set. The 1989 result was:

$$BR(K_L \rightarrow \mu\mu) = (7.6 \pm 0.5(\text{stat.}) \pm 0.4(\text{syst.})) \times 10^{-9}.$$

The preliminary combined 1988-1990 result is:

$$BR(K_L \rightarrow \mu\mu) = (6.86 \pm 0.37) \times 10^{-9}.$$

Three experiments have been active over the last few years in the search for these rare modes: AGS E780, KEK E137, and AGS E791. In general, the sensitivity to $K_L \rightarrow \mu e$ and $K_L \rightarrow ee$ events in E791 is about an order of magnitude better than that of AGS E780 and over a factor of two better than the KEK experiment. The number of $K_L \rightarrow \mu\mu$ events are about 8 and 200 in AGS E780 and KEK E137, respectively, in comparison with about 700 in E791 (1988 - 1990 three year total).

Overview of the New Experiment

The new experiment will improve upon E791 by more than an order of magnitude in sensitivity and set a limit on $K_L \rightarrow \mu e$ below 2×10^{-12} if no signal is observed. At this sensitivity, we should observe several $K_L \rightarrow ee$ events. The key features of the new experiment are:

- A lengthened decay volume.
- High rate tracking detectors.
- Enlarged detector apertures due to a new magnet configuration. 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 parallel to the beam direction. (This parallelism is used in forming the trigger.) The events that are 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, are not accepted in this magnet configuration.
- A beam stop, or plug, which is located in the upstream dipole magnet (96D40) to stop the neutral beam.
- A new Čerenkov counter and an instrumented iron muon filter.
- A reconfigured muon rangefinder.
- Improved triggers.
- Increased acceptance.

The layout of the new experiment is shown in Fig. 1. Below, several of these improvements are discussed.

Precise tracking is essential in this experiment since background rejection relies on precise kinematic reconstruction. The E871 drift chambers will present difficulties largely in the module immediately upstream of the plug in the new geometry. Neglecting any increased rate from neutrons or photons originating in the plug, the instantaneous intensity will increase by a factor between 4 and 6 due to the increased beam flux and longer vacuum decay volume. The chambers ran at rates in excess of 10 MHz in E791 and drew about 50 μ amps of current. The two detectors upstream of the beam-plug will consist of 0.5 cm straw tube drift chambers. Gas with a high drift velocity will be used in all drift chambers. The combination of smaller cell size and faster gas will permit the tracking detectors to operate efficiently with eight times higher rate as in the E791 drift chambers.

The use of two sequential magnets in a $K_L \rightarrow \mu e$ search is critical, since the decay in flight of a π (from K_{e3}) inside the magnet of a single magnet spectrometer could simulate false $K_L \rightarrow \mu e$ events. The second magnet permits an independent momentum measurement, which is very powerful in rejecting such events. In the new geometry, the sequential magnets will be tuned to provide a net p_T -kick of 220 MeV, which will cause accepted $K_L \rightarrow \mu e$ events to have both charged tracks parallel to the beam direction downstream of the second dipole. However, rather than have two relatively weak fields providing a total p_T -kick of 220 MeV, the first dipole will "over-bend" ($\Delta p_T = 440$ MeV) and be corrected in the second dipole ($\Delta p_T = -220$ MeV), so that tracks will traverse a much larger total $\int \mathbf{B} \cdot d\ell$. This permits a much better determination of track momentum. The optics of the system of dipole magnets will enhance the acceptance of the spectrometer. We plan to reuse the larger of the two dipole magnets used in E791 (96D40) as the upstream dipole in the new experiment. A second large dipole magnet (100D40) satisfying our needs has been obtained from FermiLab.

The most novel feature of the new experiment involves placing a beam dump, or plug, inside the spectrometer to stop the neutral beam and the bulk of secondary particles that are created within it. This will reduce the rates due to K_L decays and neutron interactions which would otherwise occur in the detectors far downstream of the beam plug position. The advantages of this new approach are: (1) the acceptance is improved a factor of 2.1 because there is no longer a need for the downstream detectors to have an opening between them through which the neutral beam passes, (2) the beam plug will lead to reduced the rates in the downstream detectors, (3) particle identification should be cleaner, owing to the much lower rates in the lead glass and muon detectors, (4) the parallelism of tracks from 2-body decays will provide a large suppression in the Level 1 trigger rates (allowing more time per event for the online processor) and make it easier to group signals from trigger counters, the Čerenkov counter, and the muon system, (5) the radiation dose on the lead glass will be reduced by more than an order of magnitude, and (6) making detectors continuous across the beam centerline will

eliminate the degradation of performance that typically occurs near detector edges (*e.g.*, side leakage of showers in the lead glass, multiple scattering of muons into the beam region in the muon steel or rangefinder). A great deal of effort has gone into designing and testing the beam-plug. This will be discussed in the next section.

Good particle identification is critical in a $K_L \rightarrow \mu e$ search, because the major backgrounds involve misidentifying either one or both of the charged daughters in the copious $K_L \rightarrow \pi e \nu$ decay. In E791, electron identification was accomplished with a threshold Čerenkov counter and a lead glass array, where muon identification was done with a scintillator hodoscope behind an iron wall and a muon rangefinder (in which muons below about 6 GeV were stopped, allowing a comparison between measured upstream momentum and range). For the new experiment, each of these devices has been upgraded, rebuilt, or reconfigured to improve performance.

The Čerenkov counter is of the atmospheric-pressure, gas threshold type, and will allow us to separate electrons from pions and muons. It will cover an area of about 4 square meters, centered on the beam line, and have low mass, so that multiple scattering is small. To reduce accidental coincidences, signals from the fast photomultiplier tubes will be used in the trigger which will require the x -positions of the hits in the Čerenkov counter and trigger counters be consistent.

The new Čerenkov counter is expected to have higher efficiency than the E791 counter (98% versus 89-90%) due to careful attention to optical design and execution, mirror quality, light funnel shape and reflectivity, selection of phototubes and wavelength shifter. It will also have more segmentation (32 versus 16 cells) and lower knock-on probability (mainly due to less mass in the upstream detectors). The beam-plug-test showed that special attention must be paid to shielding the tubes from the ambient flux of neutrons and photons to avoid excess rates in the Čerenkov counter.

The lowest momentum at which muons were accepted in E791 was 1.5 GeV/c. In the new experiment, we have instrumented the meter of steel which follows the lead glass array with layers of scintillation counters. This will permit a lower (1 GeV/c) muon momentum threshold which will increase the acceptance by about 10%. The instrumented muon filter also improves our ability to trigger on muons and provide good timing information on muon tracks that project into the muon rangefinder (which provides effectively no time information because drift times are long and the hits are latched). The transverse coverage of this device is roughly 2 m by 2 m, centered on the beam in both x and y . Our group has the main responsibility for this device. The details of the design are given later.

The muon rangefinder¹² in E791 consisted of two separate detectors on either side of the beam. Each consisted of marble (and some aluminum) slabs (2.25 m horizontal and 3 m vertical) with extruded aluminum drift tube chambers interspersed at intervals that provided a constant $\Delta p/p$ resolution of 10% for stopping muons. There were 13 pairs of x and y planes of these chambers on each side of the beam. Comparing the measured muon range to that expected from the momentum measured in the magnetic spectrometer upstream provides rejection against pion

decay downstream of the magnets.

In the new geometry, the muons from accepted $K_L \rightarrow \mu e$ and $K_L \rightarrow \mu\mu$ decays enter the muon identification detectors parallel to the beam direction so that the transverse extent of the muon coverage need not be as large as in E791 so that only one side of the muon rangefinder is required. This frees 13 detector planes which are used to increase the segmentation, so that roughly 5% resolution in $\Delta p/p$ will be obtained. We will also use some of these chambers to extend the range of momentum covered to ≥ 8 GeV.

One of the clearest strengths of this experiment over E791 is the improvement in the triggering. Our group has recently taken over responsibility for the implementation of the new trigger for the 1993 engineering run. More will be said about the trigger below. Briefly, the important features are: (1) The parallelism condition will provide a large suppression of semi-leptonic decays and will be relatively insensitive to accidentals and noise triggers. (2) Due to the parallel trajectories of triggering tracks, it will be easy to impose tight constraints on associated particle identification (Čerenkov and muon filter) signals. (3) Rates in the downstream trigger planes and particle identification detectors from genuine charged tracks will be considerably suppressed by the plug. In addition, singles rates will be lower in the muon counters even though the beam intensity increases by a factor of four.

The acceptance of the new detector has been calculated using Monte Carlo. Overall a factor of two improvement over E791 is expected. This arises from a number of sources including the larger decay volume, the new magnets and parallel-to-beam trajectories for the $K_L \rightarrow \mu e$ tracks, and the use of the central regions of the detectors (with beam plug). We have investigated the impact of a wider beam plug on the overall acceptance and find that only a 5% change in acceptance results from a 13% change in plug width.

Sensitivities and Backgrounds

The sensitivities for the new experiment are scaled from a well-understood (1989) data set obtained in E791. The new experiment depends on increased acceptance, running at higher beam intensity, and on a variety of improvements to individual systems which will improve efficiencies, reduce deadtimes, etc. The separate factors are listed in Table IV.

The decays $K_L \rightarrow \mu e$, $K_L \rightarrow ee$, and $K_L \rightarrow \mu\mu$ have different acceptances and are affected differently by changes in particle identification efficiencies. The relative improvements in the sensitivities for each decay channel are listed in Table V, these results being derived from Table IV. The expected sensitivities for the new experiment are also shown.

In a high sensitivity experiment background rejection is of paramount concern. For example, the copious $K_L \rightarrow \pi e \nu$ followed by $\pi \rightarrow \mu \nu$, provides an abundant source of $K_L \rightarrow \mu e$ -like events. These are rejected by requiring no missing transverse momentum, eliminating trajectories with kinks (*i.e.*, π decay), and determination of invariant mass which is a maximum of 489 MeV for the false event

	E791 1989 Data	New Experiment	Increase
$K_L \rightarrow \mu e$ acceptance	0.0113	0.0242	2.14
$K_L \rightarrow ee$ acceptance	0.00873	0.0224	2.57
$K_L \rightarrow \mu\mu$ acceptance	0.0149	0.0283	1.90
Protons on target	3.8 Tp	15 Tp	3.95
L1 trigger efficiency	0.72	0.95	1.32
L3 trigger efficiency	0.64	0.95	1.48
Cerenkov electron efficiency	0.89	0.96	1.08
PBG electron efficiency	0.95	0.97	1.02
Running efficiency	0.875	0.92	1.05
Running time	17 weeks	38 weeks (2 years)	2.24

Table IV: Improvement factors of the new experiment over the 1989 E791 run.

	E791 1989 Data	Improvement	Proposal
$K_L \rightarrow \mu e$ 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

Table V: Sensitivity of the new experiment.

mentioned here. Another background source is misidentification of the π as an e and the e as a μ in the $K_L \rightarrow \pi e \nu$ decay. Therefore precise kinematic event reconstruction and particle identification is essential. Monte Carlo simulations for the new detector with tracking in the decay volume, redesigned drift chambers and new magnets indicate that some improvement in resolution will result. In addition to improved resolution, other reasons why background rejection in the new experiment should be better than in E791 include the following: (1) The larger magnetic field in the upstream dipole will minimize the effect from pion decay in the downstream dipole. (2) Finer rangefinder segmentation ($\Delta p/p \simeq 5\%$) will provide better discrimination against downstream pion decays. (3) Better discrimination of pions against electrons should be possible with both the Čerenkov counter, which will have a lower knock-on probability and higher segmentation, and the lead glass, which will have improved resolution. (4) The lower rates in the muon systems with the beam plug will considerably reduce the probability of mistaking an electron for a muon. We are therefore reasonably optimistic that backgrounds can be suppressed to necessary levels.

The E871 Beam Plug

The critical feature of the new experiment is the beam-plug that is located inside the first spectrometer magnet. It must stop the neutral beam: photons, neutrons and K_L 's; it must reduce the rates in the downstream particle identification detectors. Since drift chambers will be placed very close to the beam-plug, the plug must prevent the secondary particles, produced from the high-energy neutral beam particles, from escaping and causing excess rate in the chambers. The plug must accomplish all this with a minimal transverse extent; any increase in the plug width beyond 40 cm causes a loss of acceptance.

The design and testing of the beam-plug was a major effort for our group during the last two years. Optimization of the design was performed using a simulation program, called CALOR89, from Oak Ridge National Laboratory. The beam-plug was extensively tested at Brookhaven during the 1991 AGS proton cycle. In addition to rate measurements using the E791 detectors, we built several special detectors to measure the number and energy-spectrum of the neutrons that were produced by the plug. These detectors (Bonner spheres, liquid scintillators, and ^3He counters) provided data which allowed us to identify the source of drift chamber rates and to test the Monte Carlo program. Our group was responsible for these special detectors and the acquisition and analysis of the data provided by them.

Beam-plug Design

The ideal material for the central part of the beam-plug is tungsten. It has an extremely short hadronic interaction length, 9.6 cm, which is surpassed only by very expensive materials such as platinum. In addition to its short hadronic interaction length, tungsten has two other important properties. First, it has a large inelastic cross-section for neutrons down to energies of 1 MeV. Since, for each incident high-energy hadron, hundreds of "boil-off" neutrons are produced with energies less than 10 MeV, it is important to attenuate them before they interact in the drift chambers via (n,p) scattering in the argon-ethane gas. A second useful property of tungsten is its short electromagnetic interaction length. Although, with a $Z=74$, it is not as effective per electron as Pb ($Z=82$); the higher density of tungsten causes it to have a shorter attenuation length than Pb.

For neutrons with energy below 1 MeV, elastic scattering from hydrogen is the most effective method for moderating the neutron energy. Materials with a high density of hydrogen, such as polyethylene or water, are usually doped with small amounts of boron or lithium because of the high absorption cross-section of these elements for thermal neutrons. One disadvantage of boron, however, is that a 477 keV photon is usually produced in the neutron capture process. These photons can be attenuated by surrounding the neutron-capture material with Pb.

The beam-plug can be crudely designed using these materials; a core of tungsten surrounded by a hydrogen-dense material, doped with an element with a large capture cross-section for thermal neutrons, which is itself covered with a layer

of Pb to attenuate photons. The exact design is much more difficult because the transverse width that can be used is limited to less than 40 cm. Therefore, we must balance the amounts of each material so that the induced drift chamber rates are minimized.

The optimum beam-plug was designed using the simulation package CALOR89, which consists of four different parts. The hadronic interactions are simulated with FLUKA at high energy and by HETC at lower energy (< 5 GeV). Photons and low-energy neutrons produced in these interactions are stored. The neutrons are then transported, using MORSE, down to thermal energies. Photons that are produced in this code are added to the photons from the hadronic interactions and are transported using EGS4. The probabilities for the particles that escape the beam-plug to interact in the drift chambers is then calculated; this permits us to quantify the effects of varying beam-plug parameters.

For a production angle of 2.75 degrees, the ratio: neutrons: K_L is approximately 20:1. In addition, the neutrons produce more secondary particles since they tend to be more energetic than the K_L 's. The input to the Monte Carlo simulations therefore included only the neutrons. The incident neutron energy spectrum was generated using GEANT and had an average energy of 12 GeV.

Beam Plug Test Results

The optimized 1991 beam-plug was installed at BNL during a 10 week test run from April-June, 1991. That test affirmed the feasibility of the beam plug concept. Nearby detector rates were determined and we obtained information concerning the effects of a variety of shielding methods. The most important measure of the beam plugs performance is its effects on the rates in the various detectors. Rates in the E791 detectors were measured during the test. As can be seen in Table VI, the particle identification counters generally had much lower rates after the beam-plug was installed. The only exception was the Čerenkov counter which had a marginal increase in rate. The rates doubled for drift chambers near the beam-plug which, when the beam intensity increases by a factor of four, means that the new tracking chambers will have to handle eight times the rate are the E791 drift chambers. This will be accomplished by using straw detectors with diameters half as large as the cell size in the E871 detectors and by using gas with a faster drift velocity than argon-ethane.

Although the 1991 tests proved that the detector rates were low enough for E871 to succeed; our photon, neutron, and charged particle measurements showed that the neutron induced drift chamber rates were lower than either the rate due to photons or charged particles. Results from the Monte Carlo and the 1991 test run both indicated that higher density materials on the sides of the beam-plug, where we were using polyethylene because of its ability to moderate neutrons, could further reduce the drift chamber rates.

During 1992 several more prototype beam-plugs were built and tested in the neutral beam. Zirconium hydride, pressed together with borated polyethylene,

E791 Detector	Ratio (with plug/without plug)
Drift Chamber 2	1.5
Drift Chamber 3	1.9
Drift Chamber 4	2.2
Drift Chamber 5	1.2
Trigger Counter 1	1.6
Cerenkov counter	1.1
Trigger Counter 2	0.46
Lead-glass Array	0.20
Muon Hodoscope	0.15
Muon Rangefinder	0.10

Table VI: The effect of the beam-plug on the rates in the E791 detectors displayed as the ratio of rates (with/without) the beam-plug.

replaced some of the borated polyethylene. The physical placement of the ZrH_2 for the tests was similar to that of the final configuration. In brick form, this material has a higher density than the borated polyethylene it replaces while maintaining a very high hydrogen content for neutron moderation. The ZrH_2 polyethylene has a density of 3.7 g/cm^3 as opposed to roughly 0.95 g/cm^3 for the 0.5% borated poly, and its hydrogen content is $7.3 \times 10^{22} \text{ atoms/cm}^3$ as compared to that of $6.6 \times 10^{22} \text{ atoms/cm}^3$ for the poly.

Another major plug design change was the addition of large amounts of dense materials on the side of the plug and also on the inside of the magnet. In 1991 tests, it seemed that the addition of an inch of copper on the side of the plug made a surprising difference in the rates. The 1992 tests therefore included several tests where a large amount of dense material was added.

One of the plug modification consisted of replacing the outer one inch of plug poly with one inch of lead. Yet another modification consisted of placing one half inch of lead on the sides of the magnet. The effects of each of these plug modifications were generally quite positive, and helped to finalize designs of the E871 beam stop. Since zirconium hydride proved successful in 1992 as did the full one inch of lead on the sides of the beam stop, these features were incorporated into the final design. Beam stop tests also lead to the incorporation of better beam monitoring devices, due to the problems encountered in normalizing the data from these tests.

With the plug optimization completed, the finalized plug was constructed in early February during magnetic field mapping of the new E871 spectrometer. The tungsten core of the plug is actually a tungsten alloy (of primarily copper). Although the manufacturer claims a magnetic permeability (μ) of less than 1.05, the large amount of metal made it unclear that the field lines would be unaffected by

its presence. The level of sensitivity of the E791 spectrometer was such that even a 1% percent discrepancy in the field (about 80 gauss) has a non-negligible effect on the reconstructed masses. Thus the metallic core of the plug was installed and field maps were made very near the plug. These maps were then compared with the field maps made before the plug was installed, and it was shown that indeed the field was unaffected to the level of a few gauss in roughly 8.5 kgauss.

The 1993 plug, shown schematically in Fig. 2, looks much the same as the 1992 version. New materials were purchased to replace those that had become damaged over the years or to fully implement successful tests. These new materials included thin sheets of borated silicon, one inch lead for the sides of the plug, one half inch lead placed near the coils, and 44 new bricks of borated zirconium hydride polyethylene. Figs. 3-4 are photographs of the beam plug before it was disassembled for final installation in the E871 setup.

The metal core of the plug had been in since February, but the outer layers were installed in late May of 1993. The E871 spectrometer and detectors were placed at about this time, and the engineering run in the summer of 1993 provided the first tests of the new detector elements. The beam stop was certainly tested as well, with beam on target rising at times to 15 Tp. Data was accumulated for the prototype straw chambers near the beam plug, and the initial analysis of their rates looks promising.

A considerable amount of beam plug data analysis has been done over the past year. In 1991 over 1200 data tapes were made, and of these about 800 were taken to study the rates in the various E791 detectors. In 1992 another 330 tapes were made, of which 220 were for rate studies. Data were accumulated for all ninety-four beam stop modifications at all five standard field strengths. Analysis consisted of replaying runs and extracting the pertinent data, weeding out runs showing problems, and combining similar runs to increase statistics. The E791 drift chambers were of primary interest, and the 'weeding out' process included identifying hot channels, dead channels, or various intermittent problems. All of these data have now been fully analyzed.

Instrumented Muon Filter

Construction and installation of the Instrumented Muon Filter (IMF) was completed in June 1993. The IMF was fully tested during the just completed engineering run (Summer, 1993). The IMF consists of 6 planes of scintillators (X0,X1,X2,Y0,Y1,Y2) separated by 26 iron plates and 16 marble slabs. Interspersed, and extending beyond the IMF, are 49 Muon Range Finder (MRG) gas counters distributed at intervals of 5% in muon momentum. The combined IMF and MRG detectors can determine muon range for momenta between 1.0 and 9.76 GeV/c. A schematic drawing of the IMF configuration is shown in Fig. 5.

The four IMF planes X1,Y1,X2, and Y2 consist of scintillator bars and photomultipliers reused from E791; they are placed at muon ranges corresponding to 0.75, 1.5, 2.8, and 5.8 GeV/c. X1 and X2 contain 11 vertical scintillator bars (see

Fig. 6) with photomultipliers at each end. Y1 and Y2 have 14 horizontal bars with a single tube (see Fig. 6). These scintillator planes have much better timing characteristics than do the MRG panels. The MRG system simply provides a latched bit for a 150 ns time window. All IMF photomultiplier outputs go to fast TDCs and the time resolution is about 1 ns. Also, outputs from X1 go to ADCs for independent energy information.

The planes X0 and Y0 are used also for the muon trigger. The spatial widths of the individual X0 and Y0 scintillators were chosen so that these counters could be incorporated into a "parallel" trigger. Thus, the planes are symmetrically divided along the beam axis, with X0 containing 18 vertical bars with photomultipliers on each end (see Fig. 6), and Y0 contains 18 horizontal bars with one photomultiplier on a single end of each (see Fig. 6). These planes are located at the position corresponding to a muon range of 1.0 GeV/c. A photograph of the top of the IMF near X1 (arrow) is shown in Fig. 7.

During the Summer 1993 engineering run the overall performance of the IMF was evaluated and found to be satisfactory.

Trigger Logic

One of the greatest improvements of E871 over E791 is the reduction in trigger rates obtained by requiring tracks to be parallel to the beam axis. This not only reduces accidental triggers dramatically, it strongly suppresses the triggers caused by semi-leptonic K_L decays. The parallel trigger requirement is applied both at the Level 0 trigger, which just includes the trigger scintillation counters, and at the Level 1 trigger, which includes the particle identification detectors (Čerenkov and IMF). We expect the Level 1 trigger rate in E871 to be lower than the E791 rate even though the beam intensity will be much higher. Our group has been responsible for installing the new trigger for the 1993 engineering run which will be discussed below.

The trigger scintillation counters (TSCs) consist of two sets of counters placed 2.9 meters apart. The upstream counter has only vertical slats, 32 on each side of the beam axis, with photomultiplier tubes on each end. The downstream counter has identical vertical slats plus 64 horizontal slats on each side of the beam axis. Each scintillator slat is 3 cm wide. The logic for the Level 0 trigger is as follows:

1. Four custom made logic modules (L0XX) produce an output indicating a coincidence between the upstream and downstream vertical TSCs. The four modules cover 4 regions: the upper tubes on the left side, the lower tubes on the left side, the upper tubes on the right side, and the lower tubes on the right side. The logic is programmable using standard CAMAC commands so that we can choose the degree of parallelism. We expect that we will require a coincidence between the j 'th downstream slat and one, or more, of the j 'th ± 2 upstream slats. The output of each module 'ORs' four slats together to form eight outputs. These eight sections correspond to the position and size of the Čerenkov mirrors and the IMF scintillators.

2. The output from the discriminators on the 64 horizontal scintillators on each side of the beam form the input for another pair of custom made logic modules (L0Y). This module simply produces 16 outputs that are the 'OR' over four adjacent counters.
3. A coincidence of the outputs from the L0XX and L0Y modules generates an output from a pair of L0XY modules, one for each side of the beam axis. This module accounts for the difference in the light propagation time in the vertical counters by delaying each signal from the horizontal counters by the proper amount. In this way very narrow time widths, approximately 10 ns, can be used which greatly suppresses accidental triggers.
4. The signals from the L0XY modules that indicate a valid parallel track on the left or right side are then combined with signals from the tracking chambers, the Čerenkov , and the IMF in a pair of L1 trigger modules, again one for each side of the beam axis. The Čerenkov signals come directly from the discriminators but the IMF signals go through a coincidence module similar to the L0XY module. For both particle identification detectors we are able to select the width required for a valid L1 trigger. Because of multiple scattering in the IMF we will likely have a loose parallelism requirement, probably ± 2 slats.
5. Finally, the outputs from the left and right L1 trigger modules become the input for the final L1 trigger module. A total of 16 physics triggers, each with a separate prescale factor, can be selected at any time so that normalization data can be acquired along with the rare decay data. The output of this module is the L1 trigger which is then 'ORed' with various calibration triggers so a single output generates all of the ADC gates and TDC starts needed to digitize the data.

Trigger Results

During the 1993 engineering run all of the L0 trigger modules were in place and we verified that they worked as expected. We also measured the L0 trigger rates at beam intensities nearly as high as we expect to have during the experiment. The trigger modules that use signals from the tracking chambers and particle identification detectors were still under construction at the time of the run.

An event satisfies the parallelism logic if tracks on both sides of the detector are parallel within the selected range. To verify that the trigger logic works as intended all permutations of hits in the trigger counters on each side are found and the difference in the positions at the upstream and downstream TSCs are calculated. The smallest difference on each side is assumed to have caused the L0XX coincidence for that side. The side that has the larger difference determines whether the event should have passed the trigger logic. In Fig. 8 this quantity is shown for non-parallel triggers and for a parallel (± 3) trigger. In the latter case

only events with this difference equal to 0,1,2, or 3 should have caused a trigger. As can be seen from the figure this is true for 95% of the events. The other 5% were most likely caused by an accidental hit in one TSC that was too early to register in the TDC. The rejection of non-parallel (semi-leptonic decays and accidentals) is approximately a factor of four for this trigger. Other rates are shown below.

For short periods of time during the engineering run we acquired data at our proposed beam intensity of 15 Tp or four times the E791 intensity. Most of the trigger rates given in Table VII were measured at 10 Tp but have been scaled up to 15 Tp. For comparison the E791 L0 rate was about 1 MHz at an intensity of 4 Tp.

Trigger selection	Trigger rate (kHz)
Non-parallel	375
Parallel $\pm$ 3 slats	86
Parallel $\pm$ 2 slats	55
Parallel $\pm$ 1 slats	31

Table VII: L0 Trigger rates measured during the 1993 engineering run. Rates are scaled up to our proposed beam intensity of 15 Tp.

Even the non-parallel E871 L0 rate, at four times the beam intensity, is much lower than the E791 L0 rate because K_L decays in the 6 meters between the first magnet and the upstream TSC no longer occur since the beam-plug stops the neutral beam. We expect to obtain another factor of seven reduction in L0 rates by using the $\pm$ 2 parallelism.

The new L1 logic will further reduce the trigger rates although here the gains will not be as large as in E791 where the inclusion of signals from particle identification detectors and tracking chambers lowered the trigger rate from 1 MHz to 8 kHz. In E871 we expect the reduction to be from 55 kHz to approximately 3 kHz.

There are two reasons for the more modest reduction. First, much of the rejection in E791 was due to the tracking chamber logic which eliminated the K_L decays downstream of the vacuum decay region. In E871, as mentioned above, the beam-plug prevents most of these decays from generating a L0 trigger. The second major difference between the experiments is that the muon trigger plane (the IMF in E871) has been moved from 1.5 GeV/c to 1.0 GeV/c to increase the sensitivity of the experiment. However, the number of pions that "punch-through" the iron to the muon trigger plane increases from 1% to 7% making the mis-identification of a pion as a muon more likely in the trigger. These events will be easily rejected in the analysis because the range of these tracks will not be consistent with the expected range of a muon.

The rest of the new logic modules for the trigger will be built before the end of 1993 which provides several months for installation and debugging before the

physics run begins in the March, 1994. This trigger work will be the major effort for our group in the coming year.

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Figure Captions

Figure 1: Plan view of the E871 detector.

Figure 2: A sectional view of the 1993 beam plug.

Figure 3: Photograph (side view) of beam plug for E871.

Figure 4: Photograph (end view, showing entrant cavity) of beam plug for E871.

Figure 5: Schematic drawing showing of the instrumented muon filter (IMF). It contains 6 scintillator planes and iron absorbers.

Figure 6: Counter configurations for the 4 types of planes that comprise the instrumented muon filter (IMF).

Figure 7: Photograph of top of IMF region of E871 detector. Only the scintillator plane X1, which is marked by the arrow, is can be seen in this photograph.

Figure 8: The magnitude of the difference between the track position in the upstream and downstream trigger counters. The side (right or left) with the larger difference determines whether the event satisfies a parallelism trigger. That value (in units of TSC slats) is plotted for (a) non-parallel triggers and (b) parallel (± 3 slats) triggers.

Figure 1

- Tungsten
- Polyethylene (B)
- Flex-Boron
- Copper
- Lead
- Polyethylene (Li)
- Zirconium Hydride

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

X1

Figure 7

Larger delta X

Larger delta X

4.4 AGS E888: Search For The H Dibaryon

(G. W. Hoffmann, J. McDonough, S. Worm;
BNL; UCI; UCLA; Princeton; Stanford; Temple; Texas; William and Mary;
R.D. Cousins, A.J. Schwartz, spokesmen)

Summary: The experiment was a two phase search for the H -dibaryon (a six-quark $uuddss$ state). The first was a decay search; it searched for the 2-body decay, $\Lambda \rightarrow p\pi^-$, where the Λ is from the decay $H \rightarrow \Lambda n$, where the H is produced in the target. The second was a dissociation experiment which searched for two Λ 's that are produced by diffractive dissociation:

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

where A is a target nucleus in the dissociator and H^* is an excited H with a mass large enough to permit it to strongly decay to $\Lambda\Lambda$.

No six quark states other than the deuteron have been discovered despite many predictions and searches. Theoretical analysis suggests that the most promising candidate is a $uuddss$ spin and isospin singlet state proposed by Jaffe¹, and known as the H particle. Unlike the deuteron, it is viewed as having all six quarks with similar spatial wave functions. The presence of three distinct flavors works in favor of a bound H . A simple way of explaining this is due to Lipkin:² quarks with unlike flavor can be in states symmetric in color-spin resulting in an attractive interaction; the more unlike quark pairs, the greater the binding. An additional factor is at work in predictions of stable strangelets and strange quark matter;³ the strange quark is distinguishable and hence not forced into higher energy states by the Pauli principle. The H is the simplest member of this family of proposed objects.

The mass of the H has been calculated in the bag model,¹ in the Skyrminion picture,⁴ and in lattice QCD.⁵ In most calculations $M_H < 2M_\Lambda$, i.e. the H is bound. The state of theory however is such that it cannot provide definitive answers concerning the existence, the mass, and correspondingly the lifetime of the H in the near future. A calculation of the H lifetime has been made by Donoghue *et al.*⁶ assuming the H to be an SU(3) flavor singlet. This is reasonable for sufficiently strong binding. Fig. 1 shows the predictions as a function of M_H (as re-plotted by Ref. 7). The lifetime changes as the various thresholds are crossed, but is in all cases many times longer than the lambda lifetime.

One promising method for detecting an H bound state is to search for Λ 's arising from $H \rightarrow \Lambda n$ and $H \rightarrow \Sigma^0 n$, $\Sigma^0 \rightarrow \Lambda\gamma$ decays. When kinematically accessible, the H branches to Λn and $\Sigma^0 n$ approximately 20% and 40% of the time, respectively, and $Br(\Sigma^0 \rightarrow \Lambda\gamma) \simeq 100\%$. The lambdas produced can be reconstructed from 2-track events with the tracks assigned proton and pion rest

masses. The reconstructed vertex z -position depends upon the H lifetime and may be significantly farther downstream than vertices from prompt lambdas. Observing such a z distribution would be a strong indication of H production.

This search for 2-body Λ decays was similar to the search for 2-body $K_L \rightarrow \mu e$ decays successfully completed by E791. The detector is shown in Fig. 2. Both spectrometer magnets and all 5 drift chamber stations were active, providing high rejection against π -decay background by requiring that the momentum measured in the front spectrometer matches that measured in the rear. All particle identification detectors (Čerenkov counter (CER), lead glass array (PbG), muon hodoscope (MHO), and muon rangefinder (MRG)) were also active, giving high rejection against K_{L3} decays. The only substantial change to the detector apparatus was the trigger, as we were interested in hadronic rather than dilepton decays. The topology is similar to a class of E791 $K_L \rightarrow \mu e$ decays: a high-momentum positive track (proton) in one spectrometer arm and a low momentum negative track (pion) in the other, which form a vertex in the decay tank.

Calculated values for the H -production cross section are plotted in Fig. 3 for different values of the H mass. The values represent the production cross-section needed to give one expected event in one day of running given E791's geometry and 5 Tp on target. If no candidate events are seen, the contour of Fig. 3 can be scaled upwards by a factor 2.3 to give an upper 90% confidence limit on the H production cross-section. This sensitivity assumes no background appears before the daily luminosity of 5.2×10^{40} per cm^2 is attained.

The other part of the experiment is the diffractive dissociation search. The single diffractive dissociation process,

$$H + A \rightarrow X + A \rightarrow \Lambda \Lambda + A,$$

belongs to a large class of similar interactions for which universal characteristics have been established. Here A is a target nucleus in the dissociator (hydrogen or carbon in our case), and X can be considered an excited H whose mass is sufficiently high to decay strongly to $\Lambda\Lambda$. As shown by the Rockefeller group⁸ and reviewed by Goulianos,⁹ the diffractive part of hadron-proton interactions at high energy is consistent with

$$\frac{d^2\sigma}{dt dx} = \frac{0.1}{(\text{GeV}/c)^2} \sigma_T \frac{1}{(1-x)} \exp(b(t + 0.05)) \quad (4.4)$$

for a variety of hadrons and energies. Here σ_T is the hadron-proton total cross section for the hadron in question, t is the four-momentum transfer squared, x is Feynman's scaling variable, and b is a slope parameter whose value ranges from $6/(\text{GeV}/c)^2$ to $12/(\text{GeV}/c)^2$ over a wide variety of diffractive phenomena. In the absence of further guidance, we assume that this equation applies to H dissociation as well. Estimates lead to

$$\sigma(M_{X1} < M_X < M_{X2}) = 0.46 \ln \frac{M_{X2}^2 - M_H^2}{M_{X1}^2 - M_H^2}. \quad (4.5)$$

Of course, this expression does not take into account the unknown effects of possible $\Lambda\Lambda$ resonances in or near this range of M_X , or of elastic scattering.

For M_{X1} , we use $2M_\Lambda = 2.231$ GeV, the lowest mass final state with the quantum numbers of the H . For M_{X2} , we conservatively use the sum of the proton and Ξ masses, 2.260 GeV. In this narrow 29-MeV range of diffractive masses, the intermediate state X should decay to $\Lambda\Lambda$ 100% of the time. For higher masses, the branching ratio falls as the ΞN (and eventually $\Sigma\Sigma$) channels compete. We thus estimate that $\sigma(H + p \rightarrow \Lambda\Lambda p)$ in this range of M_X varies from 0.04 mb to 0.1 mb as M_H varies from 1.9 to 2.1 GeV/c². For H masses closer to threshold, the cross section is bigger, though of course not singular as our simple formula would imply.

We label the four-momenta of the H , target proton, excited state X , and recoil proton as P_H , P_{p1} , P_X , and P_{p2} , respectively. Then $t = (P_X - P_H)^2 = (P_{p2} - P_{p1})^2$, (negative by convention), and $s = (P_H + P_{p1})^2 = (P_X + P_{p2})^2$. The kinetic energy T of the recoil proton is given exactly by

$$T = \frac{-t}{2M_p}. \quad (4.6)$$

Since t is universally distributed according to $\exp(bt)$, the recoil kinetic energies are distributed according to $\exp(-2bM_p T)$, i.e., $\exp(-T/(60\text{MeV}))$ for $b = 9/(\text{GeV}/c)^2$. Thus the recoil protons have a characteristic kinetic energy of 60 MeV, which corresponds to a range in scintillator of about 3 cm. (These numbers of course scale inversely with our estimate for b .) For coherent diffraction off a larger nucleus, the recoil kinetic energy is decreased.

Squaring $P_H = P_X + P_{p1} - P_{p2}$ yields

$$M_H^2 = M_X^2 - \frac{E_X t}{M_p} - 2p_X \sqrt{-t + t^2/4M_p^2} \cos(\theta) + t. \quad (4.7)$$

Here θ is the angle between the recoil proton and the system X . In principle, we may use this expression to measure the H mass using the reconstructed final state. The angle θ may be measured directly or inferred using other information and imposing transverse momentum balance. Such techniques can be checked by calculating the mass of the incoming neutron in the analogous process $n + p \rightarrow K_S \Lambda p$.

The dissociation experiment measures the momenta of all the decay products of the $\Lambda\Lambda$ diffracted state in order to eventually reconstruct the H mass. There is a distinct difference, however, between the trajectories of the protons and the pions from the lambda decays. The heavier protons tend to take away the majority of the momentum from the Λ decay and therefore stay close to the beam axis, while the pions are much softer and are easily kicked out of the beam by the magnets or lost due to narrow apertures. The E791 setup, which has beam gaps between the spectrometer arms, was not practical since all the protons travel through the gaps unobserved. In addition, in order to match the x and y views for all 4 tracks, two chambers were rotated to obtain the projected views u and v .

Our one magnet configuration is shown in Fig. 4. Here the dissociator was placed inside the existing Magnet 1 (not shown), and the left and right halves of the current third drift chamber (DC 3) were split and placed successively in z instead of side-by-side. As the protons and pions pass through Magnet 2, they are bent in opposite directions, so the downstream chambers are moved slightly off-axis. The advantage of this is twofold: we move the beam gaps away from the peak of the proton distribution which remains near $x = 0$, and we catch the soft pions which have strayed far from the beam due to the bending in the magnetic field. To enhance this effect, we moved the current DC 4 downstream where the proton and pion trajectories are well separated. The acceptance for this geometry ranged from 1.0% – 2.5%, depending upon the exact placement of the dissociator and the chambers. The optimal distance between the dissociator and the drift chambers affects both geometrical acceptance and track recognition. A large distance makes tracking easier but reduces acceptance. A short distance has the opposite problem. We acquired data with two different separation distances in case the high acceptance configuration proved unusable offline.

With the above values for our acceptance, we can now gather together all the estimates of the previous sections to determine the size of our expected signal.

For the dissociation experiment, we are particularly interested in looking for a long-lived, deeply bound H , and therefore we expect the radius of the H to be small—in the language of our coalescence calculation, we expect σ_q to be large. Our estimate of the number of H 's in the beam relative to K_L 's for such a light H was $H/K_L \sim 10^{-3}$. Combined with the typical number of K_L /TP, we find the H flux to be about 2.5×10^4 H /TP. The probability of a particular H dissociating is given by the estimated dissociation cross section times the number of protons/mb in our 10 cm thick dissociator. For $\sigma = 0.1$ mb this probability is $\sim 3.5 \times 10^{-4}$, if all available protons in the scintillator are counted. So for an acceptance of 1%, we find that the number of H 's detected per 10^{12} protons on target is given by

$$\begin{aligned} H/TP &= (2.5 \times 10^4) \times (3.5 \times 10^{-4}) \times (0.01) \\ &= 8.75 \times 10^{-2} \end{aligned} \tag{4.8}$$

Thus, with low-intensity beam of only 0.05 TP/spill on target, we estimate detection of numerous H 's, if they exist, in several days running.

During the 1992 AGS proton cycle each H experiment accumulated data for approximately 10 days. The decay experiment acquired half of the data with freon in the left Čerenkov counter to aid the proton- π^+ separation and therefore reduce background events from K_L decays. As mentioned above, that experiment, like E791, searches for a two-body decay mode. For this reason the analysis of the data is using much of the existing E791 offline analysis software with few changes. All of the 350 data tapes have been analyzed at the Pass 1 level. This analysis involved pattern recognition of tracks, fitting of tracks using the two E791 fitters, and selection of events based on a loose lambda mass cut. The minimum bias events

were stripped onto carts and used for calibration of the various E888 detectors. The resolution of the spectrometer was studied, and global magnetic field corrections were made. The exact locations of the drift chamber wires were found using magnet-off data. The wires were calibrated and their efficiency determined using these data. The TDCs and ADCs were calibrated, and the t_0 's of the TDCs were found. The MHO, Cerenkov, and MRG were also calibrated. On the basis of the new drift chamber surveys and other calibrations, it was decided to refit the raw data, and this effort is in progress. In parallel with the refitting, the H analysis code is being written and tested on the first set of data, and Monte Carlo studies of signal and background are being done.

The dissociation analysis is much more complicated. This experiment also required full calibration and surveying of the detector (including the instrumented dissociator). The analysis, which is in progress, has required the development of a separate fitting and selection code. Several passes through the data set have been made, and Monte Carlo studies of background and signal are also in progress.

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Figure Captions

Figure 1: Donoghue et al. calculation of H lifetime vs. mass.

Figure 2: The E791 detector.

Figure 3: H production cross-section corresponding to observing one H event in one day of running with 5 Tp on target.

Figure 4: Plan view of one-magnet configuration for dissociation experiment.

Figure 1

Figure 2

Figure 3

Figure 4

5 Relativistic Heavy-Ion Physics – STAR

(G. W. Hoffmann, L. Ray, D. Read, P. Jensen, S. Paganis,
X. Chen; STAR Collaboration: J. W. Harris, Spokesman)

Summary: Our group joined the STAR Collaboration in September 1992 and we are working on projects associated with the Silicon Vertex Tracker, the Time Projection Chamber, Software and Simulations, and Data Acquisition.

The main goal of the relativistic heavy-ion collider (RHIC) project at the Brookhaven National Laboratory (BNL) is to produce and study a temporary state of unconfined quarks and gluons, referred to as the quark-gluon plasma (QGP). It is hoped that a QGP will be formed through central collisions of colliding relativistic heavy ion beams, each of kinetic energies of 100 GeV per nucleon.

The existence of the QGP state of matter is conjectured, based on estimates using the MIT bag model and calculations of QCD lattice gauge theory.¹ The MIT model suggests: (1) that a system of quarks and gluons at zero baryon density and temperatures around 140 MeV will have thermal pressure comparable to the confining bag pressure, (2) for a system of quarks and gluons at zero temperature and baryon density about 5 times that of normal nuclear matter the Fermi pressure becomes comparable to the bag pressure, and (3) for conditions of temperature and baryon density beyond these limits the quarks and gluons are deconfined. A qualitative phase diagram (from Ref. 1) is shown in Fig. 1. It is thought that a QGP briefly existed during the very early moments of the universe and that a QGP exists in the interiors of neutron stars.

Secondary goals of the RHIC project include the study of (1) highly excited, very dense systems of nuclear matter, (2) hard QCD parton-parton scattering and subsequent hadronization (jet and mini-jet formation) in dense, excited nuclear matter (or possibly in the QGP), and (3) spin physics in high energy (500 GeV c.m.) $p + p$ collisions. The experimental programs at RHIC will most likely study $p + p$, proton + nucleus, and nucleus + nucleus collisions. Beam particles will range from protons and light ions (such as ^4He) to Au; beam energies will extend to 100 GeV/A, thus delivering up to 200 GeV c.m. total energy for each NN colliding pair.

The RHIC experiments will require for each collision the detection, momentum analysis, and particle identification of many charge particles including $e^\pm$, $\mu^\pm$, $\pi^\pm$, π^- , K^+ , K^- , p , $\bar{p}$, d , $\bar{d}$ as well as neutral particles including K_s^0 , ϕ , Λ , and $\bar{\Lambda}$, (through their charged particle decays) along with multiply strange particles Ξ^- and Ω^- and possibly “open charm” channels in the form of the D-mesons. The ability to measure hyperon, strange meson, and perhaps charmed meson production is important to attaining some of the goals of the RHIC project. The short decay lengths (2 - 8 cm) for hyperon and strange mesons and the very short decay

lengths of the D-mesons (0.01 - 0.03 cm) present particular challenges to detector design and construction at RHIC. Another challenge for RHIC detector design is to have the ability to study correlation between identical bosons (Hanbury-Brown-Twiss effect) which will require the accurate tracking of low momentum particles.

STAR (Solenoidal Tracker at RHIC) is one of the two large detectors to be used at RHIC. We joined the STAR collaboration in September 1992. The collaboration includes over 200 scientists, engineers, and staff who are engaged in the design and construction of this \$40M (baseline cost) detector. The main design criteria for STAR (see Fig. 2) is that it provide a flexible system for tracking all charged particles produced at mid-rapidity for $|\eta| < 1$ (η is pseudorapidity and is defined by $\eta = -\ln[\tan(\theta_{c.m.}/2)]$) for central Au + Au collisions at beam energies up to 100 GeV/A, with accurate momentum determination, particle identification, and secondary vertex track reconstruction. The detector must be able to detect, momentum analyze, and identify low p_T charged particles as well as high p_T particles.

At present, however, there are no known unique signatures that signal the formation and subsequent hadronization of the QGP. Several suggestions have been made as to possible signatures of the QGP. These include: (1) anomalous heavy quark production in A + A collisions at very high energy, (2) the occurrence of a high temperature bosonic gas region of large spatial extent along the beam direction, and (3) rapid event-to-event fluctuations in the global parameters for a critical beam species and energy.

This uncertainty leads to an unusual challenge for the design and construction phase of the RHIC detector systems because this effort is underway now in order that the detectors will be ready near the year 2000 when RHIC comes on line.

A schematic diagram of STAR is shown² in Fig. 2. The detector consists of a silicon vertex tracker (SVT), a time-projection chamber (TPC), an electromagnetic calorimeter (EMC), a time-of-flight system (TOF), an external time-projection chamber (XTPC), a warm coil solenoidal magnet, front-end electronics (FEE), a data acquisition system, and a multi-level trigger system. The cylindrical design ensures full azimuthal coverage, with momentum determination for $|\eta| < 2$, and particle identification for $|\eta| < 1$. The TPC, a partial SVT, FEE, DAQ and the magnet constitute the baseline detector of STAR. A unique feature of STAR is that it will allow measurement of global properties (temperature, entropy, total flavor production, etc.) as well as correlations between the global parameters on an *event-by-event* basis. Completion of the SVT along with the TOF, EMC and XTPC are upgrades which require additional funding.

Our efforts on the STAR project have been associated with SVT Research and Development, Software and Simulations (SAS), TPC Research, Development and Construction, and DAQ Research and Development. Our specific efforts are discussed in more detail in the following subsections.

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Figure Captions

Figure 1: Temperature and baryon density phase diagram. The region of ordinary nuclear matter is indicated by the shaded area.

Figure 2: Perspective view of the STAR detector.

Figure 1

Figure 2

5.1 Silicon Vertex Tracker

The purposes of the Silicon Vertex Tracker (SVT) are (1) to enable very accurate determination of the position of the primary collision vertex, (2) to determine the location of secondary vertices from the decays of heavy particles to a position resolution of about $100\ \mu\text{m}$, (3) to permit the tracking of low p_T charged particles well below the $150\ \text{MeV}/c$ cut-off of the TPC, and (4) to substantially improve the momentum resolution that would result from using just the TPC. The large number of charged tracks through the SVT requires a position resolution of nearly $25\ \mu\text{m}$. The SVT must also be of minimal mass in order to minimize secondary particle production, photon conversion and Coulomb multiple scattering.

The present SVT design has three concentric barrels of very thin ($300\ \mu\text{m}$) silicon drift detectors (SDD) held in place by a light weight structure made of Be. The SDDs are grouped into ladders and arranged so as to provide 100% coverage over the full 2π azimuthal range and pseudorapidity range $|\eta| \leq 1.4$. The SVT design as suggested in the STAR conceptual design report (CDR) is shown in Fig. 1. Other considerations (such as thermal stability, calibration, radiation hardness, technical difficulties, and cost) may affect the final details, such as number of SDD's, SDD shape and orientation, tiling, electronics placement, and cooling.

Figure Caption

Figure 1: Upper portion: Schematic view of the SVT detector. Lower portion: View of partially assembled SVT detector showing the individual SDDs in the ladder arrangement.

Silicon Vertex Tracker (SVT)

No Scale

Figure 1

5.1.1 Test Stand/Trigger/Data Acquisition for In-Beam SDD Tests

Summary: We have designed and constructed a test setup for in-beam testing of the Silicon Drift Detectors; we have assembled an SVT mini-DAQ for use during these tests and have made improvements and additions to the basic DAQ software package.

The Silicon Drift Detectors (SDDs) for the STAR Silicon Vertex Tracker (SVT) are currently in the research and development stage. When several of the final prototype SDD's are available, their realistic capabilities will be evaluated through in-beam tests using beams of minimum ionizing particles. In principle, these tests can be done at a variety of accelerator facilities such as the AGS at BNL, TRIUMF at Vancouver, or LAMPF at Los Alamos. As presently envisioned, a realistic test will require at least three fully instrumented SDDs (positioned serially along a test beam line); the test will determine the tracking capabilities of the detectors, their spatial resolution, two track resolution, noise, temperature effects, etc.

Fig. 1 shows a schematic of the test apparatus that has been designed and constructed for the SDD in-beam tests. The system contains 5 scintillators for forming the trigger. Scintillators V1 and V2 have 1 mm wide slots (horizontal and vertical respectively) whose overlap provides a square opening of 1mm by 1mm. These scintillators are mounted on remotely controlled motor-driven linear slides with optical encoders for precision remote position readout, and the motion for each slit (vertical for horizontal slit, and horizontal for vertical slit) allows the 1 mm square aperture to be placed at any horizontal or vertical position with respect to the beam "line". Thus, a coincidence among the no-aperture thin scintillators S1, S2, and S3, taken with anticoincidences from V1 and V2 will provide a clean trigger for the 3 SDDs (SDD1, SDD2, and SDD3) that are positioned as shown in Fig. 1. The SDD's themselves are mounted in aluminum boxes which are attached to precision lab jacks with rotary platforms; these are mounted on precision translation stages which attach to precision optical rails. Thus, precise internal alignment of the 3 SDD's can be achieved mechanically with ease through use of optical techniques. In addition, the optical rails are attached to a large platform which is mounted on Thompson shafts and has independent horizontal and vertical motion; here motion is also through remote control of motor-driven linear slides with remote readout optical encoders. The entire apparatus is controlled remotely via a 486 computer through use of a Windows 3.1 executable (on top of MS-DOS 5.0). The setup is very user friendly and allows complete mouse control of the apparatus. Photographs of the SDD test apparatus are shown in Figs. 2-4. Fig. 5 is a photograph of the 486 Monitor which shows the self-explanatory nature of using a mouse to move the components of the apparatus.

Our group also has taken on the responsibility for the data acquisition (DAQ)

system to be used for the SDD in-beam tests as well as STAR SVT DAQ in general. Copies of the DAQ system developed at the Lawrence Berkeley Laboratory (LBL) for SDD development and testing are being made at both the University of Texas and Wayne State University. This system is based on use of a Motorola 68040 single board computer (SBC) and uses VxWorks, a high-performance real-time operating system and a powerful development environment for real-time applications. A schematic of this system is shown in Fig. 6. The system uses a modified readout card from the CERN NA35 experiment as well as an unmodified receiver card from NA35. The modification required for readout card is that the clock for the Switch Capacitor Arrays (SCAs) be changed from 20 MHz to 40MHz. The preamplifier/shaper electronics are provided by the Brookhaven National Laboratory and the readout/receiver cards are provided by the Lawrence Berkeley Laboratory. The remaining equipment was purchased by Texas. This includes a Sun SparStationLX which serves as the host computer. Final integration of this system, at Texas, is currently in progress.

We have made contributions to the basic DAQ package. We have modified the NA35 cluster finder and written a basic hit finder (a type of zero-suppression routine) and integrated the two into the DAQ system. We have also modified the SVT DAQ's pad monitor program which provides on-line event visualization for SVT test data; these modifications include an important pedestal subtraction subroutine.

Figure Captions

Figure 1: Schematic of SVT test beam apparatus.

Figure 2: Photograph of SVT test beam apparatus.

Figure 3: Closeup photograph showing optical rail, translation stages, and rotary jacks used for alignment of the SDDs.

Figure 4: Photograph of the SVT test beam apparatus viewed along the beam axis.

Figure 5: PC Monitor display used for mouse control of SVT test apparatus.

Figure 6: Schematic of SVT mini-DAQ system.

Figure 2

Figure 4

Figure 5

SVT Mini-DAQ

Figure 6

5.1.2 Silicon Drift Detector Development Work

Summary: SVT Research and Development Work done at LBL which we have assisted in includes: (1) study of p-type silicon for the SDD's, (2) study of thermal effects for the SDD's, and (3) dE/dx studies for particle identification with the SVT.

p-Type Silicon Detectors

The original design for the silicon drift detectors (SDD) for the SVT utilized n-type semiconductor material. We are assisting in exploring a new design based on p-type silicon. The advantages of p-type over n-type semiconductor are (1) the drift velocity of the conducting holes is slower than that for the conducting electrons in n-type material; this facilitates improved timing and the subsequent spatial resolution of the detector, and (2) p-type silicon is easier to obtain and less expensive than n-type silicon. The new detectors are nearly ready for testing at the SVT lab at LBL. Figs. 1-2 show the new design of the p-type SDDs in the anode region.

Thermal Effects

The thermal properties of the silicon drift detectors to be used in the SVT critically affect the accuracy of the position determination of hits in the SDDs. This is due to the sensitivity of the drift velocity to temperature. It is therefore important to know the overall temperature under realistic operating conditions as well as the temperature gradients and fluctuations with time.

For these measurements two silicon wafers of the STAR1 geometry were tested with and without gas flow cooling. Both wafers were n-type silicon. Temperature was measured using a YSI 44201 thermistor glued to the surface of the silicon. Absolute uncertainty of the thermistor is $\pm 0.15^\circ\text{C}$. The thermistor monitored the surface temperature at one point as a function of time, for varying applied voltages, and with and without cooling (dry nitrogen gas flow at 200 cc/min). The results in Figs. 3 and 4 show that with cooling the SDDs achieve thermal equilibrium much faster and produce more temperature stability. The fluctuations with and without cooling are shown in Fig. 5 for 1500 V. The variation is less than the absolute accuracy of the thermistor.

A temperature map was made using an adjustable probe which touches the silicon surface. Measurements were made after the silicon reached equilibrium. Care was taken to insulate the entire system from air flow and temperature variations in the room. The temperature differences in $^\circ\text{C}$ relative to the coolest point are shown in Figs. 6 and 7 for measurements done without and with cooling, respectively. The largest temperature variation without cooling is 0.3°C and 0.1°C with

cooling.

Energy-Loss Studies

A simulation analysis of energy losses in the SDDs of the SVT has been conducted in order to determine the quality of the particle identification information available from the SVT. Initial results show that the SVT would be capable of separating two particle species for momenta up to the mass of the heavier particle. Such energy loss information would be useful in the SVT tracking analysis as well as in the SVT - TPC track matching analysis.

For charged particles with momenta of order several hundred MeV passing through 300 μm of Si large departures from the Landau energy loss distribution are possible. However since the typical energy losses are greater than the inner electron shell binding energy (for the K-shell this is about 2 keV) it was determined that the Landau energy loss distribution in GEANT is applicable.

In this analysis perfect GEANT tracks were used, actual path lengths through the Si determined by GEANT were calculated, GEANT particle momenta were assumed, signal loss due to long electron drift distances in the SDDs was neglected, and the SVT configuration assumed was for 3 non-tiled layers of 300 μm Si in each layer with no cooling or support structures. The energy loss was computed assuming the average of the two lower energy losses out of the three layers.

Energy losses for a sample of 1200 pions, kaons and protons with momenta from 50 to 450 MeV/c were computed. The results are shown in Figs. 8 and 9. A very good separation of pions and kaons up to 450 MeV/c and of protons and kaons up to 1 GeV/c was obtained. Three FRITIOF Au + Au events were analyzed and the resulting energy losses in the SVT versus particle momenta are shown in Fig. 10 while the particle population for two momentum bins are shown in Fig. 11. The qualitative features of Fig. 11 are also seen here. The π/p separation is good up to about 1 GeV/c while the π/K and p/K resolutions are consistent with the earlier results. Further analysis with many more Au + Au events is in progress.

Figure Captions

Figure 1: Anode region of p-type SDD showing surface conductors.

Figure 2: Anode region of p-type SDD showing drift paths of conducting holes.

Figure 3: Temperature as a function of time for applied voltages of 2000, 1500, 1000, 500 and 0.

Figure 4: Temperature as a function of time with cooling at 1500V.

Figure 5: Temperature variation at fixed point with and without cooling at 1500V.

Figure 6: Temperature map with no cooling. Values are in $^{\circ}\text{C}$ relative to coolest

point.

Figure 7: Temperature map with cooling. Values are in °C relative to coolest point.

Figure 8: Energy loss distributions for protons, kaons, and pions. Equal numbers of each species were assumed.

Figure 9: Projection onto the dE/dx axis of particles with momentum in the range 380-420 MeV illustrating the good particle separation achieved.

Figure 10: Energy loss spectrum for three FRITIOF Au + Au events. The particles at the lower left corner are δ -electrons.

Figure 11: Energy loss spectra for two momentum bins from Fig. 10.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10

Figure 11

5.2 Software and Simulations: Vector-Vector Matching

Summary: A code was written to match charged particle tracks in the SVT to those in the TPC. The code was developed using a sample of GEANT tracks with realistic STAR track densities. Further development of the code and installation into the STAR data analysis system (TAS) is in progress.

Two purposes of the SVT detector are to allow identification of secondary vertices from in-flight particle decays and to improve significantly the momentum resolution of the detector as a whole. Charged particles with momentum greater than about 150 MeV/c and $|\eta| \leq 1$ will produce tracks in both the SVT and TPC. In order for the SVT to be effective, the correspondence between the set of SVT tracks and those in the TPC must be determined. Since from 2000 - 4000 tracks are expected in a central Au + Au event, and because the SVT outermost detector layer and the TPC innermost pad row are separated by about 40 cm, the problem of determining which SVT and TPC tracks belong to the same particle is non-trivial. The problem is further complicated by decays which occur between the SVT and the TPC, errors in the track finding process, particle knock-out in the detector material, etc.

The previous algorithm combined SVT track finding and SVT - TPC track matching. TPC tracks were extrapolated inward, accounting for multiple Coulomb scattering (MCS), and connected to hits in the SVT, layer by layer, starting with the outermost layer. This method suffered from the increasing density of tracks as the TPC tracks were extrapolated inward and their positions smeared by MCS.

In the present method the SVT tracks are extrapolated outward and the TPC tracks extrapolated inward (both into the region between the two). The code assumes that track identification and fitting with helical trajectories has been done. Extrapolated helical trajectories are compared at an imaginary cylindrical surface. The distance out from the beam axis for the matching check can be anywhere between the SVT and TPC, roughly from 10 to 50 cm. The track position and momentum direction at the matching radius are smeared due to MCS and errors in the parameters of the helix. Energy loss effects were considered and found to be less important; so they were not included. The criteria used to decide if two tracks correspond to the same particle trajectory involves the chi-square of the track z (along beam direction) and ϕ (azimuthal angle) positions and the momentum direction and magnitude at the matching radius. Hence the process is termed "vector-vector matching."

The matching program presently includes a three level algorithm. In the first step for SVT track i (SVT_i) the best TPC track match candidate is determined based on the above chi-square criteria. Similarly for TPC_j the best SVT track match candidate is found. If $SVT_i \rightarrow TPC_j$ and $TPC_j \rightarrow SVT_i$ then the code

assigns this as a matched pair of tracks. If this *bi-directional* matching condition is not satisfied then these remaining tracks are passed to the next level. In the second level the helical parameters of the remaining SVT and TPC tracks are compared and best matches are selected based on chi-square. Finally a third level matching condition is applied to the (few) remaining tracks. These are cases which have undergone considerable scattering in the detector, either MCS or nuclear scattering. In this final level track intersections in regions of material are checked.

The matching code has been applied to a FRITIOF-GEANT generated sample of primary tracks (those originating from the primary collision point) for a Au + Au central collision at 100 GeV/A. The matching results are shown in Table VIII. The matching efficiency is defined as the number of correctly matched tracks divided by the total number in the sample. Optimum matching efficiency occurs at a matching radius of 40 cm. For this sample the algorithm correctly matches 99% of the tracks.

The code was also used to provide preliminary guidelines with respect to the relative positioning and alignment of the SVT and TPC subsystems. Fig. 1 shows the effects on the matching efficiency caused by transverse, longitudinal and azimuthal errors in the relative alignment between the SVT and TPC. Generally the matching results can tolerate a few mm and about 20 mrad error without degradation of the track matching efficiency.

Figure Caption

Figure 1: Effects of transverse, longitudinal (along beam direction), and azimuthal relative SVT – TPC alignment errors on the vector-vector matching efficiency.

Table VIII: Au + Au vector-vector matching efficiency for 1774 primary tracks

	Correct	Incorrect	Unmatched	Efficiency (%)
Bi-Directional Matching Only	1696	8	70	95.6
Add Helix Parameter Matching	1750	10	14	98.6
Add Track Intersection Matching	1755	16	3	98.9

Figure 1

5.3 Time Projection Chamber

Summary: We have designed and constructed the TPC Sector Assembly and Test stands. A request to the University for funds to create a STAR fabrication and staging area, next to the main machine shop, has been approved. Our shop personnel are doing 1-2 man-years/year of fabrication work associated with TPC baseline projects. Several of our students spent Summer 1993 at LBL working on TPC Research and Development projects.

The central Time Projection Chamber (TPC) is the main component of the STAR detector and is designed to fulfill many of the objectives of the basic physics research program to be done at RHIC.

The TPC (see Fig. 1) is a continuous tracking detector capable of handling high multiplicity events. It determines the momenta of individual particles by tracking them through a solenoidal magnetic field, and it identifies them by making multiple energy loss measurements. The active gas volume of the TPC is bounded by coaxial field cage cylinders with instrumented pad plane end-caps at both ends. A high voltage membrane at the center creates an E field, such that ionization electrons drift towards the end-caps. The end-caps contain thin-gap, multiwire proportional chambers (MWPC) in which the primary signal electrons are amplified by avalanche multiplication at the anode wires. Image charges are induced on an array of pads located behind the anode wires and are recorded as a function of time. For each track segment, the drift time provides one coordinate, while the induced signals on the pad rows provide the coordinates in the plane of the MWPC.

The TPC project requires a considerable amount of Research and Development (R&D) effort, and it requires fabrication of many components that are necessary for the realization of a working detector.

We have started some TPC construction projects at Texas. Fig. 2 is a photograph of a prototype TPC sector assembly and test stand designed at Texas and fabricated in our Physics Department Machine Shop. This stand has been delivered to LBL and currently is being used to assemble and test the first prototype outer sector. The shop is making 5 outer sector stands and 5 inner sector stands for Spring delivery. We have also started construction of wire frame carts for the TPC project; a prototype (built at LBL) is shown in Fig. 3. The scheduled completion date is May 1994. We are committed to providing 1-2 man-years/year shop support to TPC construction projects for the next several years. On the horizon are construction of lifting fixtures, aligning fixtures, and the TPC assembly and shipping stand. The University has recently allocated \$35K for creation of a large assembly and staging area for STAR construction and fabrication projects. This area, which is adjacent to our main machine shop, will be accessible by faculty,

staff, and students after regular working hours, and it will have an overhead crane on a monorail which leads to the building's loading dock. The facility will be ideally suited for large STAR construction projects.

Several of our students spent the summer (1993) at the Lawrence Berkeley Laboratory working with members of the LBL TPC group on TPC Research and Development projects. This work is briefly discussed in the remainder of this section.

Tests of wire deflection from electrostatic load

A frame was strung with wires in the configuration proposed for the STAR TPC pad plane. This test frame was used to measure electrostatic deflection of the wires as a function applied voltage. The measurements were made using a long focal length microscope and were compared to a calculation based on the GARFIELD code. The tests showed that the deflections were within the design limits set by allowable gas gain variation.

Measurements of photo-electric efficiency of metals in Ar - Methane

The photo-electric efficiency for aluminum, copper, carbon, gadolinium and hafnium cathodes in a test chamber filled with Ar 90% + CH₄ 10% were measured with light pulses from a nitrogen laser (337 nm) and a frequency quadrupled Nd-Yag laser (266 nm). This work was done to find materials suitable for electron sources in the TPC volume that could be used for spatial calibration. The preliminary results show that aluminum has a photo-efficiency of $\sim 10^{-6}$ for 266 nm UV light. With efficiencies this high it will be possible to build a relatively inexpensive calibration system based on 0.5 mm aluminum wires illuminated with a standard Nd-Yag laser system.

Calculation of electron diffusion properties in gases

Computer calculations were made to investigate the diffusion properties of He-Ethane. This gas is being considered for use in the STAR TPC, but data is not available for transverse diffusion. First the Baigi code was tested with Ar 90% + CH₄ 10%, a gas for which detailed measurements exist; then calculations for other gases were made to find both transverse diffusion parameters and the drift properties in a magnetic field. These calculations will provide initial guidance in some aspects of the TPC design and will be later checked with measurements.

Testing of gas insulating structures for field cage isolation

Test field cage structures are being used to study the feasibility of constructing the TPC field cage with a gas insulator envelope. A gas insulator is potentially simpler and cheaper than conventional insulators made of mylar film and polyurethane. Preliminary work was done in an effort to study the effects of electrode surface

details and the effects of ionizing radiation.

Figure Captions

Figure 1: Schematic of the STAR Time Projection Chamber.

Figure 2: Photograph of prototype TPC sector assembly and test stand.

Figure 3: Photograph of TPC wire frame cart.

Figure 1

Figure 2

Figure 3

6 Theoretical Work

(L. Ray)

Summary: This work includes: (1) a major review of relativistic and nonrelativistic scattering models for medium energy nucleon-nucleus elastic scattering, (2) continued development of calculations for polarized proton elastic scattering from polarized nuclear targets, in particular ^{13}C and ^3He , (3) formal multiple scattering theory treatment of antisymmetrization effects for nucleon-nucleus scattering, (4) phase shift analysis of the $NN \rightarrow N\Delta$ transition, (5) development of a nucleon-nucleon interaction model based on an effective chiral Lagrangian, and (6) coupled channels Dirac analysis of elastic and inelastic proton-nucleus scattering data. Theoretical work associated with relativistic heavy-ion physics (at RHIC energies) is commencing this year and will become the primary focus of the theoretical effort starting in late 1993 and thereafter.

6.1 Review of Nonrelativistic and Relativistic Descriptions of Proton-Nucleus Scattering

A detailed review article¹ in which nonrelativistic and relativistic scattering formalisms for nucleon-nucleus scattering are discussed and applications given for many cases of proton elastic scattering at medium energies was published. This review comes at a time when parameter free theoretical predictions based on nonrelativistic and relativistic dynamics are both beginning to provide reasonable descriptions of the data.

Research in this field continues to attract widespread theoretical interest. The 40 year history of this field attests to the fact that microscopic studies of a single nucleon's interaction with a nucleus relate to a fundamental problem in nuclear physics: a description of the complicated many-body scattering process (nucleon + nucleus) solely in terms of the underlying nucleon + nucleon (NN) dynamics and the structure of the target nucleus.

The review article contains pedagogical discussions of the theory and shows predictions from application of the following scattering models: (1) the nonrelativistic, density-dependent (NRDD) model,² (2) the nonrelativistic full-folding model,³ (3) the nonrelativistic Paris-Hamburg g -matrix optical model,⁴ (4) the relativistic impulse approximation (RIA) model,⁵ and (5) the relativistic meson exchange model (IA2).⁶ The principal assumptions and ingredients of each nonrelativistic and relativistic scattering calculation are summarized in Tables IX and X, respectively.

For the relativistic calculations using the IA2 interaction the positive energy projections of the NN relativistic t -matrix were directly constrained by phase shift analysis. The calculations using the NRDD interaction are based on the density dependent interaction² where the t -matrix was normalized to the newer, SP89 phase shift solution of Arndt.

The relativistic IA2 calculations used the nuclear densities described in Ref. 5. Briefly these correspond to the known proton vector density determined by electron scattering, Hartree-Fock-Bogoliubov neutron densities for the neutron vector density, and relativistic mean field densities for the scalar and tensor densities. The NRDD calculations and the NR calculations based on the Paris-Hamburg g -matrix⁴ used the above proton and neutron vector densities. For the 200 MeV, full-folding predictions³ the proton and neutron density matrices were computed from Woods-Saxon single particle eigenstates which were fitted to empirical charge density root-mean-square (rms) radii and single particle energies.

Anomalous magnetic moment (AMM) terms were included in each of the IA2 calculations. The electromagnetic spin-orbit (EMSO) potential was included in the NRDD predictions for 800 MeV for each target and for ^{40}Ca and ^{208}Pb at 500 MeV. EMSO effects are not expected to be important for the remaining cases. Two-body correlation contributions were also included in the NRDD calculations. The relativistic optical potential correlation contributions were not included in the IA2 or the RIA calculations since these effects are small.

In Figs. 1 - 9 the relativistic and NR model predictions for $p + ^{16}\text{O}$, ^{40}Ca and ^{208}Pb at 200, 500 and 800 MeV are compared with differential cross section ($d\sigma/d\Omega$), analyzing power (A_y) and spin rotation (Q) data. The NR density dependent results² are indicated by the solid curves. The NR results based on the Paris-Hamburg g -matrix⁴ are shown by the dashed-dotted curves. The NR full-folding predictions³ are represented by the dotted lines, and the relativistic IA2 observables⁶ are shown by the dashed curves.

At 200 MeV the NR calculations using the Paris-Hamburg g -matrix give about the right amount of structure for the differential cross sections and correctly account for the damping of the diffractive structure for ^{40}Ca and ^{208}Pb near $q \cong 2 \text{ fm}^{-1}$. The NR full-folding results provide a reasonable description of the $p + ^{16}\text{O}$ and ^{40}Ca differential cross sections but tend to have a little too much structure. The IA2 differential cross sections are fairly good but also display too much structure, particularly for $p + ^{208}\text{Pb}$. The analyzing powers predicted by all three models are qualitatively successful; all three models provide good descriptions of the spin rotation data. Overall, there is no strong preference for either the relativistic or the NR approaches at this energy.

The relativistic IA2 and NRDD-EMSO curves for $p + ^{16}\text{O}$, ^{40}Ca and ^{208}Pb at 500 MeV are shown in comparison with data in Figs. 4 - 6. The IA2 predictions accurately reproduce the angular positions of the diffractive minima and the overall slope of the differential cross section data. The NRDD cross sections have the correct diffractive shapes; however, they are a little too small in magnitude and

are shifted inward to smaller scattering angles relative to the data. The NRDD-EMSO model provides the better description of the analyzing power data. The NRDD-EMSO model predictions for the spin rotation parameter Q are larger than the IA2 predictions for $q \leq 1 - 2 \text{ fm}^{-1}$ and are in slightly better agreement with the data. Both models fail quantitatively to reproduce the forward angle A_y and Q data for $q \leq 1.5 \text{ fm}^{-1}$; the calculated analyzing powers tend to be too large while the spin rotations are too small. Overall, both models provide qualitative descriptions of the 500 MeV data.

Historically, 500 MeV was the energy where relativistic theories were most successful, especially for the RIA model.^{7,8} In view of the results shown in Figs. 4 - 6, this is certainly not the case for sophisticated NR scattering models and relativistic models which use covariant meson exchange theory. It turns out, in fact, that the success of the RIA model at 500 MeV was to some extent fortuitous. The gross discrepancies between the NR model predictions and data at 500 MeV, which formed the basis of an important issue in the 1980's, are no longer a relevant concern.

At 800 MeV both the NRDD-EMSO and the IA2 model predictions are in good, overall agreement with the data as shown in Figs. 7 - 9. The NR cross sections, however, display the characteristic problem with respect to angular positions of the minima and the overall magnitude and slope. The IA2 cross sections display an incorrect mass dependence — too small in overall magnitude for ^{16}O , roughly correct for ^{40}Ca , and a little too large for ^{208}Pb . The $p + ^{16}\text{O}$ analyzing powers and spin rotations of both theories display too much structure, particularly predictions of the IA2. The NR $p + ^{40}\text{Ca}$ A_y results compare well with the data at forward angles but underestimate the data for $q \geq 2 \text{ fm}^{-1}$. Both calculated $p + ^{40}\text{Ca}$ spin rotation curves are too deep at the minima. Each model provides quantitative descriptions of the $p + ^{208}\text{Pb}$ A_y data, except at the larger angles. The $p + ^{208}\text{Pb}$ IA2 spin rotations tend to be too small in magnitude.

The results shown in Figs. 1 - 9 make it apparent that a clear phenomenological preference does not exist for either the relativistic or the nonrelativistic approaches. Both methods are capable of describing qualitatively the body of medium energy proton-nucleus elastic scattering data, as represented by these 9 specific examples.

The curious result to come out of all this is the similarity between the effects on the predicted observables of medium and off-shell corrections in the NR approach and the virtual $N\bar{N}$ pair contributions in the relativistic IA2 model. We have no explanation to offer for this. Both the medium corrections and the virtual $N\bar{N}$ pair contributions are roughly proportional to the nuclear density squared. However, there is no obvious relation between the strengths of these various terms, which originate from very different sources, *i.e.* Pauli blocking, binding energy, and off-shell dependences in the two-component Pauli representation, and coupling to negative energy states in the four-component Dirac representation. The similarity which is presently found may only be coincidental and future efforts would most likely be best spent further implementing the NR formalism and providing a better

understanding of the virtual $N\bar{N}$ pair process in the relativistic models.

Developments of the nonrelativistic many-body scattering models should continue in order to learn how far traditional nonrelativistic theories can go in describing nuclear phenomenon. Systematic discrepancies, if they occur in the final analysis, probably indicate missing physics in the theory, *e.g.* Lorentz invariance, many-body forces, quark-gluon effects, etc. We must, of course, be careful to distinguish between failure of the nonrelativistic many-body approach itself, and inadequacy of some particular numerical application.

Relativistic quantum field theories with nucleons and mesons and relativistic nucleon-nucleus scattering models should also be pursued further, as such work provides important tools for dealing with the relativistic nuclear many-body problem and indicates the level at which relativistic effects might manifest themselves in nuclear systems. The relativistic scattering models reviewed in Ref. 1 provide an important step along the way towards a covariant description of nuclear physics.

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Figure Captions

Figure 1: Best nonrelativistic and relativistic theoretical predictions for $p + {}^{16}\text{O}$ elastic scattering at 200 MeV are compared with data. Predictions of the relativistic IA2 model (from Ref. 6), the NR Paris-Hamburg g -matrix,⁴ and the NR full-folding model of Ref. 3 are indicated by the dashed, dashed-dotted, and dotted curves, respectively.

Figure 2: Same as Fig. 1, except $p + {}^{40}\text{Ca}$ at 200 MeV.

Figure 3: Same as Fig. 1, except $p + {}^{208}\text{Pb}$ at 200 MeV.

Figure 4: Best nonrelativistic and relativistic theoretical predictions for $p + {}^{16}\text{O}$ elastic scattering at 500 MeV are compared with data. Predictions of the relativistic IA2 model (from Ref. 6) and the NRDD-EMSO model are indicated by the dashed and solid curves, respectively.

Figure 5: Same as Fig. 4, except $p + {}^{40}\text{Ca}$ at 500 MeV.

Figure 6: Same as Fig. 4, except $p + {}^{208}\text{Pb}$ at 500 MeV.

Figure 7: Same as Fig. 4, except $p + {}^{16}\text{O}$ at 800 MeV.

Figure 8: Same as Fig. 4, except $p + {}^{40}\text{Ca}$ at 800 MeV.

Figure 9: Same as Fig. 4, except $p + {}^{208}\text{Pb}$ at 800 MeV.

Table IX: Summary of Nonrelativistic Proton-Nucleus Optical Potential Models

Principals	Refs.	Rep.	Approx. ^a	NN Model	$\langle t \rangle$	EMSO	Medium Mods.	Correl.
Arellano Brieva Love	3	k-space	IA	Paris Bonn ≤ 350 MeV	Full-Fold. Off-shell t -matrix	no	no	no
Ray Hoffmann Coker	1,2	r-space	DD-LDA	Coup. Ch. Isobar ≤ 1 GeV	Opt. Fac. On-shell $t\rho$	yes	yes (local)	yes (local)
Von Geramb Rikus Nakano	4	r-space	DD-LDA	Paris ≤ 350 MeV	on-shell g -matrix Dir.+Ex.	no	yes	no

^aImpulse approximation (IA), density dependent interaction applied using local density approximation (DD-LDA).

Table X: Summary of Relativistic Proton-Nucleus Optical Potential Models

Principals	Refs.	Rep.	NN Invariant	π N Coupling	Exchange	Densities ^a	AMM ^b	Pauli Blocking ^c	Binding Energy ^d	Correl.
Clark, Coker, Hama, Hoffmann, Lumpe, Mercer, Ray, Serot	1,5,8	r-space	RIA	PS ^e	Included as local q -dependent term	RMF ^f scaled to (e, e)	yes	no	no	yes
Ottenstein Tjon Wallace	6	r-space	IA2 on-shell	PV ^f	explicit, angle averaged, local	RMF	yes	yes	no	no

^aRMF refers to relativistic mean field densities^bProjectile proton anomalous magnetic moment contribution^cEstimated from infinite nuclear matter calculation, no q -dependence^dMedium effects due to intermediate binding potential^eForm assumed for NN amplitude^fForm assumed for π N coupling in quasipotential model

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

6.2 Nuclear Structure and Medium Effects in $\bar{p}+^{13}\text{C}$ Elastic Scattering

Relativistic and nonrelativistic distorted wave Born approximation (DWBA) calculations^{1,2} describe the general features of the 500 MeV $\bar{p}+^{13}\text{C}$ A_{000N} and A_{00NN} data but do not fit details of the small angle data around 20° c.m. In Ref. 2 impulse approximation values for the NN effective interaction were used and a nuclear structure model containing a pure $1p_{1/2}$ valence neutron plus ^{12}C core was assumed. In this work³ the sensitivities of the predictions to medium corrections⁴ and shell-model configuration mixing⁵ were studied using the nonrelativistic DWBA reaction model.

For this application the $p+^{13}\text{C}$ optical potential is separated into $J = 0$ and $J > 0$ components, where

$$U_{\mu'\mu}^{opt} = \sum_{i=1}^A \langle \Phi_{gs,\mu'} | t_{0i} | \Phi_{gs,\mu} \rangle = U_{J=0}^{opt} \delta_{\mu'\mu} + U_{\mu'\mu,J>0}^{opt}, \quad (6.1)$$

J is the total angular momentum transfer. $\Phi_{gs,\mu}$ is the ^{13}C ground state wave function, μ (μ') is the initial (final) spin projection of the target nucleus, t_{0i} is the NN effective interaction t -matrix, and A is the number of target nucleons. In the second quantization representation $\sum_i t_{0i}$ is given by

$$\hat{F} = \sum A_{JMTT_3}^{\alpha\beta} [a_\alpha^\dagger \otimes a_\beta]_{JMTT_3} \quad (6.2)$$

where

$$A_{JMTT_3}^{\alpha\beta} = \sum_{m_\alpha m_\beta} \sum_{t_\alpha t_\beta} (-)^{j_\beta - m_\beta + \frac{1}{2} - t_\beta} (j_\alpha m_\alpha j_\beta - m_\beta | JM) (\frac{1}{2} t_\alpha \frac{1}{2} - t_\beta | TT_3) \\ \times \langle u_{\alpha, m_\alpha, t_\alpha} | t_{01} | u_{\beta, m_\beta, t_\beta} \rangle, \quad (6.3)$$

$[a_\alpha^\dagger \otimes a_\beta]_{JMTT_3}$ produces a particle-hole excitation in subshells $\alpha = \{n_\alpha, \ell_\alpha, j_\alpha\}$ and $\beta = \{n_\beta, \ell_\beta, j_\beta\}$ coupled to total angular momentum and isospin (J, M) and (T, T_3) , respectively, and $u_{n\ell j m t}$ is a single particle state. In this representation the $J > 0$ part of the optical potential becomes

$$U_{\mu'\mu,J>0}^{opt} = \sum_{\alpha\beta} \sum_{J>0, MTT_3} A_{JMTT_3}^{\alpha\beta} (J_i \mu J M | J_f \mu') (T_i T_{i3} T T_3 | T_f T_{f3}) \\ \times \langle J_f T_f || [a_\alpha^\dagger \otimes a_\beta]_{JT} || J_i T_i \rangle \quad (6.4)$$

where (J_i, μ) and (T_i, T_{i3}) denote the total angular momentum and isospin (plus z projections) of the target nucleus in the initial state. Similar quantities are defined for the final nuclear state. For elastic scattering from ^{13}C $J_i = J_f = \frac{1}{2}$, $T_i = T_f = \frac{1}{2}$, and $T_{i3} = T_{f3} = -\frac{1}{2}$. The doubly reduced (in spin and isospin) matrix elements

in Eq. (6.4) are proportional to the reduced density matrix elements (RDMEs), $\phi_{JT}^{fi}(\alpha\beta)$, obtained in shell-model calculations⁵ where

$$\phi_{JT}^{fi}(\alpha\beta) = \sqrt{\frac{2(2j_\alpha + 1)}{(2J + 1)(2T + 1)}} \langle J_f T_f \| [a_\alpha^\dagger \otimes a_\beta]_{JT} \| J_i T_i \rangle . \quad (6.5)$$

The $J = 0$ part of $U_{\mu'\mu}^{opt}$ was assumed to be the Schrödinger equivalent of the Dirac phenomenological optical potential for 500 MeV $p+^{12}\text{C}$ elastic scattering plus the scalar and time-like vector parts of the relativistic impulse approximation optical potential for the $1p_{1/2}$ valence neutron state. The NN density dependent t -matrix calculated in Ref. 4 was used for t_{0i} .

In Refs. 1 and 2 the nuclear structure model was not constrained by the $M1$ elastic form factor measured in back angle electron scattering.⁶ Therefore the Cohen and Kurath (CK) (8-16)2BME p -shell model⁵ and an empirical radial wave function were adopted and used to fit the $M1$ form factor. For comparison, calculations were also done assuming a pure $1p_{1/2}$ neutron configuration with harmonic oscillator radial wave function where the oscillator parameter was adjusted to reproduce the zero of the $M1$ form factor at $q = 1.04 \text{ fm}^{-1}$. The two radial wave functions used here and the corresponding $M1$ form factors are shown in Figs. 1 and 2, respectively.

The results for A_{000N} and A_{00NN} are shown in Fig. 3. The predictions assuming the pure $1p_{1/2}$ model with harmonic oscillator radial wave function and the NN t -matrix fixed at the zero-density value (impulse approximation) are shown by the dotted curves. The results using the CK wave functions with and without density dependence in the NN t -matrix are shown by the solid and dashed curves, respectively. Density dependent effects are small for this case while the differences due to the choice of nuclear structure models are greater, particularly for A_{000N} at the larger angles. While the overall structures of the two sets of target spin observable data are described by these predictions the peaks near 20° c.m. are inadequately explained. Predictions based on the relativistic impulse approximation DWBA model do not fit the forward angle data either.²

The present work demonstrates that medium corrections and nuclear structure effects of the type considered here are unimportant for this case, at least in the forward angle region around 20° c.m. where discrepancies between theory and experiment are greatest.

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Figure Captions

Figure 1: Radial wave functions for the $1p$ state used in the DWBA calculations. The harmonic oscillator wave function corresponding to the pure $1p_{\frac{1}{2}}$ single neutron configuration is shown by the dashed curve while the solid curve indicates the empirical wave function used with the CK shell-model.

Figure 2: Elastic $M1$ form factors (squared) in ^{13}C corresponding to the $1p_{\frac{1}{2}}$ single neutron configuration with harmonic oscillator wave function (dashed curve) and the CK shell-model with an empirical radial wave function (solid curve). The form factor is expressed in units of nuclear magnetons.

Figure 3: Nonrelativistic DWBA predictions for A_{000N} (upper part) and A_{00NN} (lower part) for 497.5 MeV $\bar{p} + ^{13}\bar{\text{C}}$ elastic scattering. Dotted, dashed and solid curves represent the results of calculations assuming the $1p_{\frac{1}{2}}$ single neutron model (no medium corrections), the CK shell-model (no medium corrections), and the CK shell-model with medium corrections, respectively. Data are from Ref. 2.

Figure 1

Figure 2

Figure 3

6.3 Predictions for $\vec{p} + {}^{13}\vec{\text{C}}$ Elastic Scattering Based on the Relativistic IA2 Effective Interaction

Theoretical analysis of the 500 MeV $\vec{p} + {}^{13}\vec{\text{C}}$ elastic scattering spin observable data A_{000N} and A_{00NN} from LAMPF EXP955 provides an opportunity to test models of the spin-flip components of the nucleon-nucleon effective interaction. Calculations based on the original relativistic impulse approximation (RIA) model and nonrelativistic models¹⁻³ produce similar results and qualitatively describe the data. However, none of these predictions are able to quantitatively fit the structure in the A_{000N} and A_{00NN} data in the forward angle region around 20° c.m., corresponding to the first minimum in the differential cross section.

Tjon and Wallace⁴ developed a relativistic impulse approximation model for nucleon-nucleus scattering based on covariant meson-exchange theory. The parameters of the interaction were adjusted to fit the experimental NN phase shifts, thereby directly constraining only the positive energy matrix elements of the Lorentz invariant NN scattering operator. Matrix elements which couple positive and negative energy nucleon states are predicted by the model and should be tested. This model for the NN scattering operator, referred to as the IA2, consists of a generalized expansion in terms of Lorentz invariant operators. It includes forty three complex amplitudes at each energy for each NN isospin channel. The IA2 interaction is unique in that it is the only relativistic effective interaction derived from a dynamical meson exchange theory.

The IA2 has been successfully used to describe proton-nucleus elastic scattering from even-even targets from 200 - 800 MeV incident proton energy.⁵ However, only a few of the IA2 amplitudes are important for proton elastic scattering from 0^+ target nuclei, leaving most of the IA2 interaction terms untested in nuclear scattering analyses. The remaining terms contain operators which, in the nonrelativistic language, induce spin-flip. The purpose of the work discussed here and reported in Ref. 6 is to test the spin-flip terms in the IA2 interaction.

Application of the IA2 interaction to the $\vec{p} + {}^{13}\vec{\text{C}}$ elastic scattering calculation is very tedious owing to the large number of amplitudes and the explicit momentum dependence of many of the Lorentz invariant operators. Furnstahl and Wallace⁷ recently developed an effective, density dependent, two-component Pauli representation for the IA2 interaction for use in nucleon-nucleus elastic and inelastic scattering calculations. This IA2 effective interaction enables accurate approximations to the exact IA2 calculation to be obtained from standard Schrödinger equation scattering models which include density dependent effective interactions.

The $p + {}^{13}\text{C}$ elastic scattering amplitude in the IA2 model is given by

$$f_{m', \mu', m, \mu}(\vec{k}, \vec{k}') \cong f_{m', m}^{core}(\vec{k}, \vec{k}') \delta_{\mu' \mu} + \frac{m}{2\pi(\hbar c)^2} \langle \chi_{C, \vec{k}', m'}^{(-)} u_{p \frac{1}{2} \mu'} | \hat{\mathcal{M}} | u_{p \frac{1}{2} \mu} \chi_{C, \vec{k}, m}^{(+)} \rangle, \quad (6.6)$$

where f^{core} and $\chi_C^{(+)}$ are the scattering amplitude and relativistic distorted wave,

respectively, corresponding to elastic scattering from the $p+^{12}\text{C}$ IA2 “core” optical potential, $u_{p\frac{1}{2}\mu}$ is the relativistic $1p\frac{1}{2}$ single particle (neutron) state in ^{13}C , μ and μ' are the initial and final ^{13}C spin projections, m_s and m'_s are the initial and final projectile spin projections, and $\hat{\mathcal{M}}$ represents the Lorentz invariant IA2 NN scattering operator. Using the results of Ref. 7 this equation can be rewritten as

$$f_{m'_s, \mu', m_s, \mu}(\vec{k}, \vec{k}') \cong f_{m'_s, m_s}^{core}(\vec{k}, \vec{k}')\delta_{\mu'\mu} - \frac{m}{2\pi(\hbar c)^2} \langle \psi_{C, \vec{k}' m'_s}^{(-)} \phi_{p\frac{1}{2}\mu'} | t_{eff}^{inel} | \phi_{p\frac{1}{2}\mu} \psi_{C, \vec{k} m_s}^{(+)} \rangle, \quad (6.7)$$

where $\psi_C^{(+)}$ is a two-component distorted wave corresponding to $\chi_C^{(+)}$, $\phi_{p\frac{1}{2}\mu}$ is the two-component $1p\frac{1}{2}$ bound state wave function, and t_{eff}^{inel} is the density dependent effective interaction corresponding to the IA2 interaction from Ref. 7. The distorted waves, core scattering amplitudes and bound state wave functions were computed as in previous work.¹⁻³

The IA2 predictions for A_{000N} and A_{00NN} are displayed in Fig. 1 in comparison with LAMPF EXP955 data.² The solid curves represent the full IA2 predictions while the dashed lines indicate the IA2 results where Dirac phenomenological f^{core} and $\psi_C^{(+)}$ were used. The differences between the solid and dashed curves demonstrate that the predicted polarized target spin observables are quite sensitive to the model assumed for generating the $p+^{12}\text{C}$ scattering amplitude and distorted wave. The overall magnitude and structure of the A_{000N} data are qualitatively reproduced by the IA2 model provided f^{core} and $\psi_C^{(+)}$ from Dirac phenomenology are assumed. On the other hand, the magnitude of the structure in the A_{00NN} data at 20° and 33° c.m. is underestimated by the IA2 model with Dirac phenomenological f^{core} and $\psi_C^{(+)}$. The full IA2 calculations fail to predict the positive peaks for both observables near 20° c.m.

It is interesting to compare the IA2 effective interaction predictions with those of the best available application of nonrelativistic multiple scattering theory. This comparison is shown in Fig. 2. The dashed curves are identical to the dashed curves in Fig. 1. The dotted curves represent nonrelativistic DWBA predictions³ (see section 6.2) where the same f^{core} , $\psi_C^{(+)}$ and $\phi_{p\frac{1}{2}\mu}$ used in the IA2 calculations were assumed but where the NN effective interaction was taken to be the nonrelativistic density dependent (NRDD) interaction from Ref. 8. Fig. 2 displays a direct comparison of the IA2 and NRDD models of the NN effective interaction with respect to scattering observables which are dominated by spin-flip amplitudes. The results are similar for both models, however the IA2 prediction for A_{000N} is in slightly better agreement with the data while the IA2 prediction at larger angles for A_{00NN} is noticeably worse than that of the NRDD model. From this work we find that the spin-flip components of the IA2 effective interaction tested here are realistic.

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Figure Captions

Figure 1: IA2 density dependent effective interaction predictions and data (Ref. 2) for 497.5 MeV $\vec{p} + {}^{13}\vec{\text{C}}$ elastic scattering target analyzing power, A_{000N} , and spin correlation, A_{00NN} . The predictions assuming the IA2 (Dirac phenomenological) core scattering amplitude and distorted wave are indicated by the solid (dashed) curves.

Figure 2: Comparison of the IA2 effective interaction predictions (dashed curves) and nonrelativistic density dependent (medium modified) predictions (dotted curves) with data for 497.5 MeV $\vec{p} + {}^{13}\vec{\text{C}}$ A_{000N} and A_{00NN} . In both calculations the same Dirac phenomenological (D.P.) core amplitudes and distorted waves and the same harmonic oscillator $1p_{1/2}$ neutron single particle wave function were assumed.

Figure 1

Figure 2

6.4 Proton Elastic Scattering from Polarized ^3He

TRIUMF has recently provided data for $\vec{p}+^3\vec{\text{He}}$ elastic scattering at several energies from 200 to 500 MeV.¹ Included are the differential cross section, the analyzing power, the target analyzing power A_{000N} , and the spin correlation A_{00NN} . The data extend out to about 5 fm^{-1} of momentum transfer.

The nonrelativistic DWBA scattering model² was used to generate predictions for the polarized target spin observables. The $p+^3\text{He}$ optical potential was separated into $J = 0$ and $J = 1$ components (where J is the total angular momentum transfer); the $J = 0$ part was described phenomenologically while the $J = 1$ part was computed from the $s_{\frac{1}{2}}$ wave functions and the full, spin-dependent NN t -matrix. The $J = 0$ part of the optical potential was obtained by fitting the $\vec{p}+^3\text{He}$ differential cross section and analyzing power data using Dirac phenomenology.³ This, in turn, provided the $J = 0$ part of the $p+^3\text{He}$ elastic scattering amplitude and the distorted waves for use in the DWBA. The single particle wave functions were determined by fitting the measured $M1$ form factor in ^3He (Ref. 4) where the ^3He nucleus was assumed to be an antisymmetrized product of $s_{\frac{1}{2}}$ single particle states. Meson exchange currents were ignored. The NN t -matrix was used on-shell and was obtained from the Arndt SP89 phase shift solution.

The NR-DWBA predictions and data for 500 MeV $\vec{p}+^3\vec{\text{He}}$ elastic scattering are shown in Fig. 1. The predictions are reasonable for angles up to 40° c.m. (about 3 fm^{-1} momentum transfer) but differ significantly from the data at larger angles. The discrepancies might be due to unrealistic wave functions and/or NN t -matrices at large momentum transfer, meson exchange currents, multiple scattering effects, etc.

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Figure Caption

Figure 1: Nonrelativistic DWBA predictions for 500 MeV $\vec{p}+^3\vec{\text{He}}$ A_{000N} and A_{00NN} in comparison with the data from Ref. 1.

$p + {}^3\text{He}$ 500 MeV, NR-DWBA

Figure 1

6.5 Pauli Blocking Effects for Nucleon-Nucleus Scattering

Theoretical predictions for nucleon-nucleus scattering are customarily based on multiple scattering formalisms in which the projectile nucleon - struck target nucleon two-body subsystem is antisymmetrized and the target wave function is antisymmetric with respect to the nucleon constituents. Pauli blocking of the struck target nucleon in intermediate scattering states is implicitly included in standard optical potential calculations which consistently include terms through second-order in the projectile - target nucleon scattering t -matrix. In recent work¹ we organized the multiple scattering expansion of the fully antisymmetrized nucleon-nucleus optical potential so as to make explicit, corrections to the standard optical potential due to *Pauli blocking of the projectile nucleon* in intermediate scattering states.

In nonrelativistic multiple scattering formalisms^{2,3} (Watson and KMT) it is assumed that the projectile particle is distinguishable from the nucleon constituents of the target nucleus. The identity of the A target nucleons is incorporated into the theory by projecting antisymmetric target nucleus states in all intermediate scattering states in the formal definition of the projectile-nucleus scattering t -matrix. Expansions of the optical potential for elastic scattering in terms of quasi-two-body t -matrices result in a linear term which is summed over the A target nucleons and a second-order term which is proportional to two-body correlations in the target nucleus wave function⁴ plus higher order terms. The quasi-two-body t -matrices are in reality $(A+1)$ -body operators, but for the leading Born term only depend on the coordinates of the projectile and *one* active target nucleon. Intermediate scattering states of the active target nucleon used in constructing these quasi-two-body t -matrices are not restricted with respect to the states occupied by the other $(A-1)$ target nucleons, *i.e.* the quasi-two-body t -matrices are *not* Pauli blocked. Even so, this formalism accounts for Pauli blocking of the target nucleons in intermediate scattering states by construction. Explicit Pauli blocking corrections do not appear in the final expression for the optical potential due to certain cancellations which occur among the second-order terms.⁴

Application of the Watson or KMT formalisms to the case of nucleon-nucleus scattering is usually carried out by way of the Takeda and Watson (TW)⁵ prescription. According to this procedure the unsymmetrized, nucleon-nucleon (NN) quasi-two-body t -matrices in the Watson or KMT formalisms are everywhere replaced with operators which are antisymmetric with respect to the projectile nucleon and struck target nucleon labels. Takeda and Watson argue that the leading correction to this prescription involves a three-body exchange potential which should be small and indeed calculations⁶ show that this term is negligible at medium energies.

Intuitively, however, one would not expect the simple TW prescription to adequately account for all of the effects arising in nucleon-nucleus scattering due to

the imposition of full $(A+1)$ -body antisymmetrization. In particular, Pauli blocking of the projectile nucleon in intermediate scattering states is not accounted for by simply invoking the TW procedure. Experience with Pauli blocking effects in nucleon-nucleon g -matrix calculations for infinite nuclear matter and for density dependent, effective interaction t -matrices⁷ shows that such effects can be quite important.

We have used the formalism of Picklesimer and Thaler,⁸ which incorporates full $(A+1)$ -body antisymmetrization, to study Pauli blocking corrections to the standard nucleon-nucleus optical potential. The optical potential and the resulting nucleon-nucleus t -matrix from Ref. 8 operate on *unsymmetrized* $(A+1)$ -body states where the wave functions describing the $(A+1)$ -body system are not antisymmetrized with respect to the labels of the projectile nucleon and target nucleon constituents. It is important to note that the unsymmetrized $(A+1)$ -body states referred to here and in Ref. 8 include fully antisymmetrized A -body states of the target nucleus. Dynamical effects due to projectile and target nucleon identity are therefore included in the construction of the optical potential.

The $(A+1)$ -body antisymmetrized transition operator appropriate for elastic scattering is given by

$$\hat{T} = \sum_{i=1}^A v_{0i} \bar{\mathcal{A}} (1 + G_\alpha T) \quad (6.8)$$

where v_{0i} represents the two-body interaction between the projectile (0) and the i^{th} target nucleon. Here, the unsymmetrized channel corresponds to the projectile nucleon label being (0) and the target constituent labels running from 1, 2, $\dots$ A . In Eq. (6.8) $\bar{\mathcal{A}}$ is the antisymmetrizer for the projectile nucleon and A target nucleon labels. It is given by

$$\bar{\mathcal{A}} = 1 - \sum_{i=1}^A E_{0i} \quad (6.9)$$

where E_{0i} is the exchange operator for projectile (0) and identical target nucleon (i). The unsymmetrized $(A+1)$ -body propagator, G_α , is given by

$$G_\alpha = (E - H_0 - H_A + i\epsilon)^{-1} \quad (6.10)$$

where H_0 is the projectile kinetic energy operator and H_A is the nuclear Hamiltonian. In Eq. (6.8) T represents the usual unsymmetrized scattering operator given by

$$T = \sum_{i=1}^A v_{0i} (1 + G_\alpha T) . \quad (6.11)$$

The $(A+1)$ -body antisymmetrized optical potential which generates $\hat{T}$ is defined by

$$\hat{T}' = \hat{U}' + \hat{U}' G_\alpha \mathcal{P} \hat{T}' \quad (6.12)$$

where

$$\hat{T}' = \frac{A-1}{A} \hat{T} , \quad (6.13)$$

$(A - 1)/A$ is the usual KMT scaling factor, and $\mathcal{P}$ projects the unsymmetrized elastic channel.

Introducing the free NN two-body t -matrix, t_{0i}^f , where

$$t_{0i}^f = v_{0i} + v_{0i} g t_{0i}^f \quad (6.14)$$

and g is the free NN propagator, the $(A+1)$ -body antisymmetrized optical potential can be expanded as

$$\begin{aligned} \hat{U}' = & \frac{A-1}{A} \sum_{i=1}^A \left[t_{0i}^f + t_{0i}^f \varepsilon_{0i} - t_{0i}^f g t_{0i}^f \varepsilon_{0i} + t_{0i}^f (\bar{A} G_\alpha - g) t_{0i}^f \right] \\ & + (A-1)^2 \left[\frac{1}{A(A-1)} \sum_{i \neq j} t_{0i}^f G_\alpha t_{0j}^f - \frac{1}{A^2} \sum_{ij} t_{0i}^f G_\alpha \mathcal{P} t_{0j}^f \right] \\ & + (A-1)^2 \left[\frac{1}{A(A-1)} \sum_{i \neq j} t_{0i}^f \varepsilon_{0i} G_\alpha t_{0j}^f - \frac{1}{A^2} \sum_{ij} t_{0i}^f G_\alpha \mathcal{P} t_{0j}^f \varepsilon_{0j} \right. \\ & \left. - \frac{1}{A^2} \sum_{ij} t_{0i}^f \varepsilon_{0i} G_\alpha \mathcal{P} t_{0j}^f - \frac{1}{A^2} \sum_{ij} t_{0i}^f \varepsilon_{0i} G_\alpha \mathcal{P} t_{0j}^f \varepsilon_{0j} \right] + \dots \quad (6.15) \end{aligned}$$

where $\varepsilon_{0i} = -\sum_{j \neq i} E_{0j}$. In the limit $\bar{A} \rightarrow 1$, $\hat{U}'$ reduces to the usual unsymmetrized optical potential and in the limit $\varepsilon_{0i} \rightarrow 0$ it reduces to the unsymmetrized optical potential with the TW substitution.

The terms in the first set of brackets in Eq. (6.15) include the usual “ $t\rho$ ” term plus antisymmetrization and binding potential corrections. The “ $t\rho$ ” potential corresponds to folding the free NN t -matrix with the one-body ground state nuclear density matrix. The second term in the first set of brackets represents a three-body antisymmetrization correction linear in t_{0i}^f , which was calculated in Ref. 6 and shown to be negligible for medium energies. The third term inside the first set of brackets represents a higher order multiple scattering correction to this three-body term. The fourth term in the first set of brackets represents the leading correction due to Pauli blocking of the projectile nucleon (0) in intermediate scattering states (as a result of the $\bar{A}$ antisymmetrizer) and binding potential effects on the struck target nucleon (resulting from H_A in G_α). This fourth term is the one of primary interest here.

The terms in the second set of brackets in Eq. (6.15) give rise to two-body correlation contributions while the terms in the third set of brackets represent antisymmetrization corrections to the second-order optical potential. The latter should be small and are not evaluated here.

The NN-isobar coupled channels model of Ref. 7 was used to calculate an approximation to the fourth term in the first set of brackets in Eq. (6.15). In order to do so the intractable $(A+1)$ -body operators, $\bar{A}$ and G_α , in this term were replaced by a projectile nucleon Pauli blocking factor (Q_{proj}) for infinite nuclear matter and a modified two-nucleon energy denominator ($1/e$) where the energy

of the target nucleon includes kinetic energy and binding potential contributions appropriate for infinite nuclear matter.

The projectile Pauli blocking factor for infinite nuclear matter for NN intermediate states is determined by the requirements,

$$\begin{aligned} Q_{\text{proj}}^{NN}(\vec{k}'_0, \vec{k}'_1, k_F) &= 1 \text{ if } |\vec{k}'_0| > k_F \\ &= 0 \text{ if } |\vec{k}'_0| \leq k_F \end{aligned} \quad (6.16)$$

where $\vec{k}'_0$ and $\vec{k}'_1$ are the intermediate momenta in the laboratory for the projectile and target nucleon, respectively, and k_F is the Fermi momentum of nuclear matter. The angle averaged values for Q_{proj} , assuming relativistic kinematics, are straightforward to obtain as in Appendix A of Ref. 7.

Calculations of the medium modified t -matrix (sum of the first and fourth terms in $\hat{U}'$) were done for incident laboratory kinetic energies of 320 and 500 MeV. The calculations presented here are the same as that done in Ref. 7 except for the use of the *projectile only* Pauli blocking factors rather than the *projectile and target nucleon* Pauli blocking factors. The results for the real and imaginary parts of the isoscalar spin-independent and spin-orbit NN t -matrices in the NN COM system are shown in Figs. 1-4. The values at zero density ($k_F = 0$) are shown by the dashed lines. The values corresponding to $k_F = 1.4 \text{ fm}^{-1}$ from Ref. 7 are shown by the solid lines while the new results computed here for $k_F = 1.4 \text{ fm}^{-1}$ are indicated by the dashed-dotted lines. Except for $Re(t_0^{LS})$ the density dependence is weakened by not Pauli blocking the target nucleon as would be expected. At energies above 500 MeV the binding potential corrections dominate so that elimination of Pauli blocking for the struck target nucleon will have minor effect on the density dependence computed in Ref. 7.

Based on this work we recommend that density dependent effective interactions, which are to be used for nucleon-nucleus scattering calculations in the context of a nonrelativistic multiple scattering optical potential formalism, include explicit Pauli blocking of only the projectile nucleon and nuclear binding potential effects for only the struck target nucleon.

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Figure Captions

Figure 1: Nucleon-nucleon-isobar coupled channels model calculations of the density dependent $Re(t_0)$ at 320 MeV (upper half) and 500 MeV (lower half). On-momentum-shell t -matrix elements are shown as a function of momentum transfer (q). The dashed, dashed-dotted and solid curves represent the results of calculations made with $k_F = 0.0 \text{ fm}^{-1}$, $k_F = 1.4 \text{ fm}^{-1}$ with Pauli blocking of the projectile and binding potentials acting on the target nucleon as described here, and $k_F = 1.4 \text{ fm}^{-1}$ with, in addition, explicit Pauli blocking of the target nucleon (from Ref. 7), respectively.

Figure 2: Same as Fig. 1, except $Im(t_0)$.

Figure 3: Same as Fig. 1, except $Re(t_0^{LS})$.

Figure 4: Same as Fig. 1, except $Im(t_0^{LS})$.

Figure 1

Figure 2

Figure 3

Figure 4

6.6 Phenomenological Transition Amplitudes for $NN \rightarrow N\Delta$ at 800 MeV

At intermediate energies a significant fraction of the total reaction cross section for projectile-nucleus collisions is due to excitation of the $\Delta(1231 \text{ MeV})(3,3)$ nucleon excited state. Experimental studies of Δ excitation in nuclei have been carried out using nucleon and light ion projectiles by way of the (p, p') , (p, n') , $(d, 2p)$, and $(^3\text{He}, t)$ reactions. Analogous studies have been done using pion absorption, electron scattering and photon absorption. Interestingly the Δ excitation spectra for nuclear targets are shifted with respect to that observed for ^1H targets and depend on the type of projectile used.¹ A significant part of the shifts in the Δ excitation spectra apparently depends on the dynamics of Δ excitation and propagation in the nuclear medium.¹ Spin dependence in these dynamical quantities is crucial to understanding the shifts in the positions of the Δ peak for the various reactions.¹

In previous work simple models for the $NN \rightarrow N\Delta$ and $N\Delta \rightarrow N\Delta$ amplitudes have been used such as the purely spin-longitudinal model and the mixed spin-longitudinal, spin-transverse model.¹ The latter is based on π and ρ exchange with empirical short-range interaction. In general, however, the $NN \rightarrow N\Delta$ transition amplitudes include 16 parity invariant terms,² not just one or two. Ten of the 16 terms contain rank 2 tensor spin operators. In order to further advance the theoretical understanding of Δ excitation reactions in nuclei complete two-body $NN \rightarrow N\Delta$ and $N\Delta \rightarrow N\Delta$ amplitudes are required which are consistent with nucleon-nucleon (NN) phenomenology.

The principal results of the present work reported in Ref. 3 were (1) a phenomenological $NN \rightarrow N\Delta$ transition amplitude was obtained which is consistent with the available two-body data and which is appropriate for use in DWBA calculations of Δ excitation in nuclei and (2) the importance of the rank 2 tensor amplitudes was demonstrated.

The $pp \rightarrow nX$ inclusive reaction data⁴⁻⁷ at 800 MeV were described using a partial wave expansion model with a flexible parametrization for the partial wave transition matrix similar to that used in the phase shift analysis of Ref. 6. The transition matrix parametrization incorporates phenomenological $\pi N \rightarrow \Delta$ Breit-Wigner amplitudes, allows smooth variation of the inelastic phase shift across the Δ excitation region, and includes unitarity constraints. The Δ excitation continuum was divided into discrete bins of uniform width δ_M .

For the reaction $pp \rightarrow np\pi^+$ the probable intermediate states are $n\Delta^{++}$, $p\Delta^+$, $d^*\pi^+$ and $NN\pi$ non-resonant states. From isospin conservation the $n\Delta^{++}$ dominates the $p\Delta^+$ by 9 to 1. The $d^*\pi^+$ and $NN\pi$ states are only important at lower energies. Neutron production via the reaction $pp \rightarrow n\Delta^{++} \rightarrow n(p\pi^+)$ [$pp \rightarrow p\Delta^+ \rightarrow p(n\pi^+)$] is referred to as the "direct" ["decay"] channel. For purposes of studying Δ excitation in nuclei the direct channel is preferred as in the (p, n') and $(^3\text{He}, t)$ charge exchange reactions. For this analysis the choice of kine-

matics and the selection of the outgoing neutron inclusive channel greatly enhance the dominance of the $n\Delta^{++}$ intermediate state, i.e. the direct channel; only the $n\Delta^{++}$ state was considered in the present work.

The spin projection transition amplitude is given by

$$\begin{aligned}
f_{m'_1 m'_2, m_1 m_2}^{NN \rightarrow \alpha}(\theta, \phi) = & I_f \sum_{L_i S_i} A_f \sum_{LSJ} i^{L_i - L} \sqrt{4\pi(2L_i + 1)} (L_i 0 S_i, m_1 + m_2 | J, m_1 + m_2) \\
& \times (s_1 m_1 s_2 m_2 | S_i, m_1 + m_2) (L, M_L, S, m'_1 + m'_2 | J, m_1 + m_2) \\
& \times (s'_1 m'_1 s'_2 m'_2 | S, m'_1 + m'_2) \frac{1}{k_i} \sqrt{\frac{k_i \epsilon_f}{k_f \epsilon_i}} \tilde{C}_{L, S_i, \alpha LS}^J Y_{L, M_L}(\theta, \phi) \quad (6.17)
\end{aligned}$$

where α labels the outgoing $N\Delta$ channel corresponding to the α^{th} Δ -mass bin. (θ, ϕ) are the polar and azimuthal neutron scattering angles. m_1 and m_2 are the spin projections ($\pm 1/2$) along the z -axis (incident beam direction) for the projectile and target nucleons, m'_1 and m'_2 are the corresponding spin projection quantum numbers for the outgoing particles (i.e., $\pm 1/2$ for nucleons, $\pm 1/2$ and $\pm 3/2$ for Δ), $M_L = m_1 + m_2 - m'_1 - m'_2$, L_i and S_i (L and S) are the orbital and total spin angular momentum quantum numbers in the initial (final) state, and J is the total angular momentum. Isospin factor I_f and antisymmetrization factor A_f in this equation for $pp \rightarrow n\Delta^{++}$ are given by

$$\begin{aligned}
I_f &= -\sqrt{3}/2 \\
A_f &= [1 - (-1)^{L_i + S_i + I_i}] / \sqrt{2}, \quad (6.18)
\end{aligned}$$

where I_i is the NN isospin in the initial state. The factor $\sqrt{k_i \epsilon_f / k_f \epsilon_i}$ accounts for the reduction in particle velocity in the final outgoing state due to internal excitations.

Following Shypit *et al.*⁶ the C -matrix for inelastic transitions was parametrized as (suppressing quantum numbers)

$$\tilde{C}_{NN, \alpha} = N \frac{\Gamma(M_\alpha) \sqrt{\delta_M} h(M_\alpha) k_f^{2L}}{[(M_\Delta - M_\alpha)^2 + \Gamma(M_\alpha)^2/4]^{\frac{1}{2}}} e^{i(\psi + \delta_{NN} + \delta_{N\Delta})} \quad (6.19)$$

$$\psi = \tan^{-1} \left(\frac{\Gamma(M_\alpha)/2}{M_\Delta - M_\alpha} \right), \quad (6.20)$$

where M_Δ and Γ are the resonance mass and width obtained from analysis of $\pi + N$ scattering, δ_M is the finite bin width for the discretized Δ excitation continuum, M_α is the Δ invariant mass for the α^{th} bin, δ_{NN} is the NN elastic channel phase shift, N is a normalization constant constrained by unitarity, $\delta_{N\Delta}$ is the empirical phase shift to be determined, and $h(M_\alpha)$ is a smooth, empirical function given by

$$h(M_\alpha) = 1 + a(M_\alpha - M_0) \quad (6.21)$$

with parameters a and M_0 . The latter function was needed in order to optimize the fit to the excitation function data. The empirical $\delta_{N\Delta}$ was allowed to vary across the Δ region according to

$$\delta_{N\Delta} = A_{N\Delta} + B_{N\Delta}(\psi - \pi/2) \quad (6.22)$$

where $A_{N\Delta}$ and $B_{N\Delta}$ are independent parameters.

The normalization constant N was determined by requiring

$$\sum_{\alpha} ' |2i\tilde{C}_{NN,\alpha}|^2 = 1 - \eta^2 \quad (6.23)$$

for uncoupled NN states and

$$\sum_{\alpha} ' |2i\tilde{C}_{NN(\pm),\alpha}|^2 = 1 - \eta_{\pm}^2 \cos^2(2\tilde{\epsilon}) - \eta_+ \eta_- \sin^2(2\tilde{\epsilon}) \quad (6.24)$$

for NN tensor coupled states. The summation $\sum_{\alpha}'$ includes the full Δ excitation region but excludes the NN elastic channel. Variables η and $\tilde{\epsilon}$ are the NN inelasticity and complex mixing angle and the $\pm$ signs refer to NN channels with $L = J \pm 1$.

It is advantageous to represent the scattering matrix in terms of a sum of bilinear products of spin transition operators. For $NN \rightarrow N\Delta$ this is given by:

$$\begin{aligned} f = & \mathcal{F}_{0N} S_N + \mathcal{F}_{0,qq} T_{qq} + \mathcal{F}_{0,NN} T_{NN} + \mathcal{F}_{0,qQ} T_{qQ} \\ & + \mathcal{F}_{NN\sigma N} S_N + \mathcal{F}_{N,qq\sigma N} T_{qq} + \mathcal{F}_{N,NN\sigma N} T_{NN} + \mathcal{F}_{N,qQ\sigma N} T_{qQ} \\ & + \mathcal{F}_{qq\sigma_q} S_q + \mathcal{F}_{qQ\sigma_q} S_Q + \mathcal{F}_{q,qN\sigma_q} T_{qN} + \mathcal{F}_{q,NQ\sigma_q} T_{NQ} \\ & + \mathcal{F}_{Qq\sigma_Q} S_q + \mathcal{F}_{QQ\sigma_Q} S_Q + \mathcal{F}_{Q,qN\sigma_Q} T_{qN} + \mathcal{F}_{Q,NQ\sigma_Q} T_{NQ} . \end{aligned} \quad (6.25)$$

where q is in the direction of the momentum transfer, N is normal to the scattering plane and Q is orthogonal to both. The spin operators σ , S and T correspond to $S = 1$ vector transitions for spin $1/2$ to $1/2$, $S = 1$ vector transitions for spin $1/2$ to $3/2$, and $S = 2$ tensor transitions for spin $1/2$ to $3/2$, respectively. These 16 $\mathcal{F}$ amplitudes can be obtained from linear combinations of the spin projection transition amplitudes.

The parameters of the model include M_{Δ} , Γ , a , M_0 , and the phase shift parameters $A_{N\Delta}$ and $B_{N\Delta}$. The parameters of the $\pi N \rightarrow \Delta$ Breit-Wigner amplitude, M_{Δ} and Γ were fixed throughout the analysis. The NN elastic phase shifts and inelasticities were taken from the SP89 solution of Arndt. The latter quantities determine the predicted total reaction cross section for $pp \rightarrow n\Delta^{++}$ which overestimates the measured $pp \rightarrow n\Delta^{++}$ total reaction cross section as expected since the NN inelasticities account for *all* inelastic processes including the $p\Delta^+$ channel and the nonresonant pion production channels. To correct for this the calculated transition amplitude was reduced overall by a factor of 0.9 in order to reproduce the experimental $pp \rightarrow n\Delta^{++}$ total reaction cross section of 13.3 mb (Ref. 5).

The best fits to the 800 MeV differential cross section, analyzing power, polarization transfer and spin correlation data⁴⁻⁷ are shown in Figs. 1-4 and the final parameter values are listed in Table XI. The fits shown represent the best overall compromise for the entire data set which could be achieved with the present model. Each set of data is semi-quantitatively reproduced by the model although in some cases deficiencies are apparent.

Seven of the 16 parity invariant amplitudes are nonvanishing at zero degrees. These include the three vector amplitudes $\mathcal{F}_{NN}$, $\mathcal{F}_{qq}$ and $\mathcal{F}_{QQ}$ where at 0° $\mathcal{F}_{QQ} = \mathcal{F}_{NN}$ and the four tensor amplitudes $\mathcal{F}_{0,qq}$, $\mathcal{F}_{0,NN}$, $\mathcal{F}_{N,qQ}$, and $\mathcal{F}_{Q,qN}$ where at 0° $\mathcal{F}_{N,qQ} = -\mathcal{F}_{Q,qN}$. The absolute values of the vector amplitudes $\mathcal{F}_{QQ}$ and $\mathcal{F}_{qq}$ at 0° are shown in the upper half of Fig. 5 over the mass range of the Δ excitation region by the solid and dashed lines, respectively. Similarly the magnitudes of the 0° tensor amplitudes $\mathcal{F}_{0,qq}$, $\mathcal{F}_{0,NN}$, and $\mathcal{F}_{Q,qN}$ are shown in the lower half of Fig. 5 by the solid, dashed, and dashed-dotted curves, respectively. The main point to notice is that the tensor amplitudes are comparable to or larger than the vector amplitudes. The tensor amplitudes make substantial contributions to the observables.

The transition amplitude obtained here provides the first complete phenomenological $NN \rightarrow N\Delta$ input needed in theoretical calculations of nucleon and light ion induced Δ excitation on nuclear targets.

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Figure Captions

Figure 1: Inclusive and integrated exclusive $pp \rightarrow nX$ data (Refs. 4 and 7) and $pp \rightarrow n\Delta^{++}$ results from the present partial wave expansion model (solid curves) for differential cross sections in the NN c.m. for the following cases: *part (a)* $d^2\sigma/dM_\alpha d\Omega$ at $\theta = 0^\circ$; *part (b)* $d\sigma/dM_\alpha$, neutron scattering angles integrated from 60° to 120° ; *part (c)* $d\sigma/dM_\alpha$, neutron scattering angles integrated from 120° to 180° ; *part (d)* $d\sigma/d\Omega$, mass of recoil system integrated over full Δ excitation region.

Figure 2: Integrated exclusive $pp \rightarrow nX$ data (Refs. 6 and 7) and $pp \rightarrow n\Delta^{++}$ results from the present partial wave expansion model (solid curves) for analyzing powers in the NN c.m. for the following cases: *part (a)* $A_y(M_\alpha)$, neutron scattering angles integrated from 0° to 180° ; *part (b)* $A_y(\theta)$, mass of recoil system integrated over full Δ excitation region; *part (c)* $A_y(\theta)$, mass of recoil system integrated over Δ excitation region from 1180 to 1280 MeV; *part (d)* $A_y(\theta)$, mass of recoil system integrated over Δ excitation region from 1180 to 1220 MeV; *part (e)* $A_y(\theta)$, mass of recoil system integrated over Δ excitation region from 1220 to 1260 MeV.

Figure 3: Inclusive $pp \rightarrow nX$ data from Ref. 4 and $pp \rightarrow n\Delta^{++}$ results from the present partial wave expansion model (solid curves) for the polarization transfer observables D_{NN} (upper half) and D_{LL} (lower half) at 0° neutron scattering angle.

Figure 4: Integrated exclusive $pp \rightarrow nX$ data from Ref. 6 and $pp \rightarrow n\Delta^{++}$ results from the present partial wave expansion model (solid curves) for the spin correlation observables A_{SL} as a function of M_α (upper half) with integration over all neutron scattering angles and as a function of θ (lower half) with integration over the full Δ excitation region.

Figure 5: Absolute magnitudes of calculated 800 MeV $pp \rightarrow n\Delta^{++}$ transition amplitudes at 0° . *Upper half:* vector amplitudes $\mathcal{F}_{NN} = \mathcal{F}_{QQ}$ (solid line) and $\mathcal{F}_{qq}$ (dashed line). *Lower half:* tensor amplitudes $\mathcal{F}_{0,qq}$ (solid line), $\mathcal{F}_{0,NN}$ (dashed line), and $\mathcal{F}_{Q,qN} = -\mathcal{F}_{N,qQ}$ (dashed-dotted line).

Table XI: $NN \rightarrow N\Delta$ isospin 1 partial wave couplings and best fit parameters for 800 MeV. Other parameter values are: $M_\Delta = 1231$ MeV, Γ from $\pi N \rightarrow \Delta$ analysis, $a = 0.01376$ MeV $^{-1}$, and $M_0 = 1174.6$ MeV.

NN	$N\Delta^a$	$A_{N\Delta}$ (deg)	$B_{N\Delta}$
3P_0	3P_0	81.9	-0.096
3P_1	$^3P_1, ^5P_1$	116.5, 5.17	3.32, -1.38
1D_2	$^5S_2, ^3D_2, ^5D_2$	116.3, 90.0, 63.1	0.034, 1.35, 0.245
3P_2	$^3P_2, ^5P_2$	15.6, 108.6	1.02, -1.13
3F_2	$^3P_2, ^5P_2$	0, 0 ^b	0, 0 ^b
3F_3	5P_3	-0.32	-0.57
1G_4	5D_4	20.7	0.336
3F_4	3F_4	19.7	-0.055
3H_4	3F_4	0 ^b	0 ^b
3H_5	5F_5	135.1	-0.326
1I_6	5G_6	191.3	-0.361
3H_6	3H_6	32.7	-0.46
3J_6	3H_6	0 ^b	0 ^b

^aAll other $I=1$ NN channels were neglected; $\eta(^1S_0) = 1.0$ in SP89 solution. Other possible $N\Delta$ channels were omitted.

^bFixed

Figure 1

Figure 2

Figure 3

Figure 4

$pp \rightarrow n\Delta^{++}$ at 0.8 GeV at $\theta = 0^\circ$

Figure 5

6.7 Effective Chiral Lagrangians for the Nucleon-Nucleon Interaction

During the past two years we have collaborated with Dr. Carlos Ordonez and Mr. U. van Kolck (Weinberg group, University of Texas) in the study of effective chiral Lagrangians for the NN system. While it is generally accepted that QCD is the theory of the strong interaction, it has not been shown how the nuclear force between two nucleons emerges from this fundamental interaction.

To address this problem Weinberg^{1,2} recently proposed (and Ordonez and van Kolck have extended, Ref. 3) a systematic approximation scheme based on chiral perturbation theory for pions and non-relativistic nucleons. The description is in terms of an effective Lagrangian which incorporates the symmetries of QCD, in particular *chiral symmetry*. In this approach the fundamental quark and gluon fields of QCD are projected onto the hadronic fields where the higher mass hadronic degrees of freedom are "integrated out" of the fundamental Lagrangian, resulting in an effective Lagrangian. The effects of the higher mass mesons and baryons (except the $\Delta(3,3)$ isobar) are subsumed in the contact interactions. This approach provides the most general Lagrangian for a system of low-momentum pions and nucleons which is consistent with the symmetries of QCD. This approach is *a priori* model independent and is consistent with chiral symmetry. These are the new features which make this approach to the NN interaction problem unique.

The interaction part of this effective Lagrangian can be expanded in powers of (Q/M) where Q represents the largest particle momentum considered in the problem and M is a characteristic QCD mass scale (of order of the ρ meson mass). By the method of "power counting"^{1,2} (essentially dimensional analysis) the effective Lagrangian can be systematically expanded for low energies.

At this stage our model is not intended to provide a description of NN phenomenology which is superior to others (e.g. Bonn, Paris, Nijmegen, etc.). Rather, our purpose is to first demonstrate the phenomenological capability of the approach by seeing how well the model is able to describe low energy NN data, including deuteron properties, and then study those components of the NN interaction which follow from the symmetries of QCD with respect to their effects on two-body scattering.

The lowest order effective Lagrangian in this theory is²

$$\begin{aligned} \mathcal{L}^{(0)} = & -\frac{1}{2}D^{-2}\partial_\mu\vec{\pi}\cdot\partial^\mu\vec{\pi} - \frac{1}{2}D^{-1}m_\pi^2\vec{\pi}^2 \\ & +\bar{N}\left[i\partial_0 - 2D^{-1}F_\pi^{-2}\vec{t}\cdot(\vec{\pi}\times\partial_0\vec{\pi}) - m_N - 2D^{-1}F_\pi^{-1}g_A\vec{t}\cdot(\vec{\sigma}\cdot\vec{\nabla})\vec{\pi}\right]N \\ & -\frac{1}{2}C_S(\bar{N}N)(\bar{N}N) - \frac{1}{2}C_T(\bar{N}\vec{\sigma}N)\cdot(\bar{N}\vec{\sigma}N) \end{aligned} \quad (6.26)$$

where $\vec{\pi}$ represents the isospin dependent pion vector field, N is the nucleon field, g_A is the axial coupling constant, $F_\pi \cong 190$ MeV is the pion decay amplitude, $\vec{t}$ is

the nucleon isospin operator, $D = 1 + \vec{\pi}^2/F_\pi^2$, and C_S and C_T are free parameters representing the effects of higher order degrees of freedom (heavy mesons). Derivatives of the pion field and space-like derivatives of the nucleon field are of order Q and at low momentum enable expansions in powers of (Q/M) . On the other hand, the time-like derivatives of the nucleon field are of order m_N (nucleon mass) and hence are not small. Weinberg has shown that the equation of motion for the nucleon field can be used to eliminate the $\partial_0 N$ terms,² resulting in interaction terms which can be combined with those already present in $\mathcal{L}^{(0)}$.

Ordóñez and van Kolck³ extended Weinberg's original work to include higher order (through order $(Q/M)^3$) terms in the power counting expansion of the NN interaction. The next two orders in the expansion of the Lagrangian are:³

$$\begin{aligned}\mathcal{L}^{(1)} = & -\frac{B_1}{F_\pi^2} D^{-2} \bar{N} N ((\vec{\nabla} \vec{\pi})^2 - \dot{\vec{\pi}}^2) - \frac{B_2}{F_\pi^2} D^{-2} \varepsilon_{ijk} \varepsilon_{abc} \bar{N} \sigma_k t_c N \partial_i \pi_a \partial_j \pi_b \\ & - \frac{B_3}{F_\pi^2} m_\pi^2 D^{-1} \bar{N} N \vec{\pi}^2 - \frac{D_1}{F_\pi} D^{-1} \bar{N} N \bar{N} (\vec{\sigma} \cdot \vec{t} \cdot \vec{\nabla} \vec{\pi}) N \\ & - \frac{D_2}{F_\pi} D^{-1} \bar{N} \vec{\sigma} N \cdot \bar{N} (\vec{t} \cdot \vec{\nabla} \vec{\pi}) N - \frac{1}{2} E_1 (\bar{N} N) (\bar{N} N) (\bar{N} N) \\ & - \frac{1}{2} E_2 \bar{N} N (\bar{N} \vec{\sigma} N) \cdot (\bar{N} \vec{\sigma} N) - \frac{1}{2} E_3 \bar{N} \vec{t} N \cdot \bar{N} \vec{t} \vec{\sigma} N \cdot \bar{N} \vec{\sigma} N\end{aligned}\quad (6.27)$$

$$\begin{aligned}\mathcal{L}^{(2)} = & \frac{1}{2m_N} \bar{N} \vec{\nabla}^2 N - \frac{A'_1}{F_\pi} [\bar{N} (\vec{t} \cdot \vec{\sigma} \cdot \vec{\nabla} \vec{\pi}) \vec{\nabla}^2 N + \vec{\nabla}^2 \bar{N} (\vec{t} \cdot \vec{\sigma} \cdot \vec{\nabla} \vec{\pi}) N] \\ & - \frac{A'_2}{F_\pi} \vec{\nabla} \bar{N} (\vec{t} \cdot \vec{\sigma} \cdot \vec{\nabla} \vec{\pi}) \cdot \vec{\nabla} N - C'_1 [(\bar{N} \vec{\nabla} N)^2 + (\vec{\nabla} \bar{N} N)^2] \\ & - C'_2 (\bar{N} \vec{\nabla} N) \cdot (\vec{\nabla} \bar{N} N) + \dots\end{aligned}\quad (6.28)$$

where B_i , D_i , E_i , A'_i and C'_i are undetermined parameters and $\dots$ represents other four-nucleon terms. Terms including the Δ are also included. The above interaction terms include derivative couplings, 1-loop diagrams, and $\Delta(1232 \text{ MeV})$ intermediate states.

Including terms through order $(Q/M)^3$ was sufficient for the essential elements of the low energy NN interaction to emerge from the theory. In its present form the model accounts for one-pion exchange (OPE) in the static limit plus non-static (recoil) corrections through order $(Q/M)^2$, two-pion exchange of the Brueckner - Watson type,⁴ order $(Q/M)^3$ corrections, Brueckner - Watson graphs with one Δ and with two Δ s, iterated Born graphs with one and two Δ s, static and non-static (through order $(Q/M)^2$) contact terms, and a series of new terms which follow from chiral symmetry. These latter terms are represented by the diagrams in Fig. 1. The model thus includes the usual long-range OPE potential, mid-range two-pion exchange, and short-range (contact) phenomenological terms.

The NN interaction was Fourier transformed into coordinate space where it contains local terms as well as non-local derivative $(\partial/\partial r)$ terms through second-order. The spin structure of the potential includes the usual $\vec{\sigma}_1 \cdot \vec{\sigma}_2$, S_{12} , and $\vec{S} \cdot \vec{L}$

operators along with several other parity invariant spin operators. It is also isospin dependent. At present the model includes a total of 70 individual spin, isospin, and derivative terms accumulated from the various diagrams. The model contains a total of 26 parameters for both isospin channels 0 and 1.

The non-local character of the potential required extensive modification of the NN scattering code which we have previously used to analyze NN phase shifts to 1 GeV.⁵ The NN data fitted here include the Arndt energy dependent phase shifts at 10, 25, 50 and 100 MeV along with the deuteron binding energy, magnetic moment and electric quadrupole moment. The parameters of the model were varied over a general grid to determine the rough location of the minimum in $|\chi|^2$. Following this the fits were optimized using the downhill simplex method. The best fits to the Arndt phase shifts are shown in Figs. 2 and 3, the calculated deuteron parameters are given in Table XII and the values of the 26 parameters, which are related to those shown in the expressions for $\mathcal{L}^{(0)}$, $\mathcal{L}^{(1)}$ and $\mathcal{L}^{(2)}$ above, are listed in Table XIII.

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Figure Captions

Figure 1: New one-loop NN diagrams which arise in the NN interaction from the effective chiral Lagrangian.

Figure 2: Best fits to the isospin 0 NN phase shifts of Arndt.

Figure 3: Best fits to the isospin 1 NN phase shifts of Arndt.

Table XII: Deuteron properties obtained in the present chiral symmetry model.

Quantity	Chiral Model Value	Experiment	Units
Binding Energy	2.18	2.22462 ± 0.00006	MeV
Magnetic Moment	0.8514	0.85735 ± 0.00003	nm
Quadrupole Moment	0.231	0.278 ± 0.008	fm ²
Percent <i>d</i> -state	4.97		
Asymptotic <i>d</i> -to- <i>s</i> -state ratio	0.02392		

Table XIII: Parameters of the NN chiral symmetry model.

Parameter	Value	Units
g_A	1.328	
h_A	2.030	
F_π	191.8	MeV
A_1	-0.02697	
A_2	0.04785	
B_1	2.633	
B_2	6.575	
B_3	13.60	
C_{S0}	859.8	MeV fm ³
C_{T0}	-204.0	MeV fm ³
C_{10}	197.5	MeV fm ⁵
C_{20}	0.02605	MeV ⁻¹ fm ³
C_{30}	-98.87	MeV fm ⁵
C_{40}	-0.001107	MeV ⁻¹ fm ³
C_{50}	3.183	fm ⁴
C_{60}	84.09	MeV fm ⁵
C_{70}	0.004468	MeV ⁻¹ fm ³
C_{S1}	100.4	MeV fm ³
C_{T1}	-516.9	MeV fm ³
C_{11}	117.1	MeV fm ⁵
C_{21}	0.02398	MeV ⁻¹ fm ³
C_{31}	-9.064	MeV fm ⁵
C_{41}	0.003311	MeV ⁻¹ fm ³
C_{51}	-1.369	fm ⁴
C_{61}	33.39	MeV fm ⁵
C_{71}	0.009613	MeV ⁻¹ fm ³

Figure 1

Figure 2

Figure 2, continued

Figure 3

6.8 Dirac Coupled Channel Calculations for Proton Elastic and Inelastic Scattering at Medium Energies

Coupled channel calculations for proton-nucleus elastic and inelastic scattering were done using the Dirac equation formalism in collaboration with Ohio State University and IBM.¹ The cases considered included ^{40}Ca , ^{90}Zr and ^{208}Pb at 362, 500 and 800 MeV. Both phenomenological and RIA² forms for the diagonal and coupling potentials were assumed in order to describe the elastic scattering data and the inelastic transition data to low-lying collective states. The latter were described using the collective vibrational model. The RIA diagonal and transition potentials were obtained by folding the relativistic invariant NN amplitudes with the relativistic mean field scalar and vector densities and their first derivatives, respectively. The strengths of the scalar and vector transition potentials were freely adjusted to fit the inelastic data. The Dirac coupled channel equations³ were solved numerically using the code ECIS⁴ which employs the sequential iteration method. The results were checked using the code CENITH⁵ which solves the coupled equations exactly.

The elastic scattering results are shown in Figs. 1-3 for the following cases:⁶⁻⁹ ^{40}Ca at 362 MeV, ^{40}Ca at 500 MeV, and ^{208}Pb at 800 MeV. At 362 MeV the RIA model is not adequate. Adjusting the strengths of the real and imaginary parts of the scalar and vector potentials permits much improved description of the data (dashed lines in Fig. 1) while the relativistic potential model of Murdock and Horowitz¹⁰ also produces satisfactory results. For the 500 and 800 MeV cases including multistep contributions to the elastic channel results in significant improvement in the large angle scattering predictions as seen by comparing the dashed curves (no channel coupling) with the solid curves (with channel coupling). Finally a representative sample of the many inelastic scattering calculations performed in this work is shown in Fig. 4 for $^{40}\text{Ca}(p, p')$ at 500 MeV for the first 3^- , 2^+ and 5^- states.¹¹ In general all the differential cross section data were very well fit by the RIA model and the analyzing power data (at 500 MeV) were very well described at forward angles. Multistep processes are not important for the inelastic transitions studied here as expected.

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Figure Captions

Figure 1: Large angle proton elastic scattering data and predictions for ^{40}Ca at 362 MeV. The dashed and dotted lines correspond to predictions made with adjusted and unadjusted RIA potentials, respectively, while the solid curves correspond to the relativistic Murdock - Horowitz potential. The data are from Ref. 6.

Figure 2: Large angle proton elastic scattering data and predictions for ^{40}Ca at 500 MeV. The solid and dashed lines correspond to Dirac - RIA predictions with and without coupling to the 3^- state. The data are from Refs. 7 and 8.

Figure 3: Large angle proton elastic scattering data and predictions for ^{208}Pb at 800 MeV. The solid and dashed lines correspond to Dirac - RIA predictions with and without coupling to the 3^- state. The data are from Ref. 9.

Figure 4: Cross sections and analyzing powers for inelastic transitions to the first 3^- , 2^+ , and 5^- states in ^{40}Ca for 500 MeV incident protons. Solid curves represent the Dirac coupled channels RIA collective model fits. Data are from Ref. 11.

Figure 1

Figure 2

Figure 3

Figure 4