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Experiments for the 21st Century

BNL 52512
FORMAL REPORT

AGS-2000
Experiments for the 21st Century

Proceedings of the Workshop Held at Brookhaven National Laboratory May 13-17, 1996

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Laurence Littenberg
Brookhaven National Laboratory
and
Jack Sandweiss
Yale University
Editors

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Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

NTIS price codes:
Printed Copy: A06; Microfiche Copy: A01

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INTRODUCTION

General Comments on the AGS and its Evolution

The AGS has a vital and interesting potential for new research. The reasons for this are a fortunate concomitance of the energy chosen for the AGS and the steady stream of technological advances which have both increased the intensity and flexibility of the AGS beams, and the capability of detectors to use these new beam parameters.

The energy is well above the strange particle threshold and indeed is close to the optimum for the production of the most intense beams of modest energy or stopping strange particles. Similarly the energy is close to optimum for the production of large fluxes of pions or their interesting progeny, the muons. An intensity of 10^{14} protons/pulse will be available.

The advances in detectors have taken many forms but perhaps the most significant advances have been fueled by the great development of computer and related electronics capabilities. It is really these advances which lie behind the remarkable growth in the data handling capabilities of modern detectors. This development is far from over and will continue into the foreseeable future. The growth in data "absorption" has in turn led to an ever increasing reach for fundamental measurements.

Another change over the lifetime of the AGS is the advent of the Standard Model, in no small part due to discoveries at this machine. There is thus a firm framework for interpreting the results of particle physics experiments. This makes a number of possible AGS measurements critical tests of our understanding, i.e., it creates "frontiers" in the areas of precision measurements and searches for rare processes.

Promising Areas for Future AGS Physics

The physics potentials of the future AGS program can be roughly divided into three broad areas.

1. Fundamental Elementary Particle Studies (based on rare kaon decays, rare muon processes and searches for new particles)

We note that the potential of the rare kaon decay program will be far from exhausted by the time of AGS-2000. These experiments include the measurement of $K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^0 \nu\bar{\nu}$ which are now predicted rather precisely by the Standard Model in terms of the CKM matrix elements. The latter is particularly interesting since its branching ratio is proportional to square of the CKM CP-violation parameter, η, and offers the cleanest and most direct way of determining this quantity. Although measuring $K_L \to \pi^0 \nu\bar{\nu}$ is experimentally quite challenging, there are very real advantages in a low-energy approach exploiting the AGS. This is also true of $K^+ \to \pi^+ \nu\bar{\nu}$. The K^+ and K_L decays taken together can give a very clean determination of the same sin(2 ß) that is one of the main objects of the forthcoming study of B meson decays using the B factories currently under construction. Details are given in the summaries. We note that these possibilities arise because of the advances in beams and detectors mentioned above.

In addition to the experiments which address specific predictions of the Standard Model, there are very interesting experiments which would be sensitive to the predictions of more speculative models. The search for T-violating muon polarization in $K_{\mu 3}$ is a particularly timely example, since an experiment that is very sensitive to non-CKM CP-violation in this mode is possible at the AGS. Such CP-violation is thought to be necessary to explain the observed baryon asymmetry of the universe.

There are also very attractive potential AGS-2000 experiments such as a search for $\mu \to e$ conversion, which probe beyond the Standard Model outside the kaon system. Recently, it has been realized that the ratio of usable muons to targeted protons at the AGS could be made much larger than previously assumed. Together with certain new ideas on experimental configuration, this makes possible advances in sensitivity of several orders of magnitude. $\mu \to e$ conversion is particularly interesting in light of recent developments in supersymmetric GUTs, which predict that an experiment with the sensitivity attainable at AGS-2000 would observe this process over a wide range of the possible parameter space. Although there is a larger element of "risk" in such experiments it is important to realize that if successful, they would have a great impact. The history of physics also shows that the unexpected does happen and indeed the healthiest program is one which maintains a diverse reach for a broad spectrum of physics possibilities.

2. Non-Perturbative QCD

This area has come to be regarded as lying somewhere between high energy physics and (modern) nuclear physics. It includes many topics which in an earlier day would clearly be regarded as particle physics. Wherever one places it in the physics administrative spectrum, it remains true that a rich and important set of physics studies remains to be done. These can be grouped as follows:

a) Spectroscopy of mesons and baryons: In particular there have been several important recent developments in the area of meson spectroscopy. Lattice gauge theory is approaching the point where it can adjudicate amongst extant glueball candidates, and firmly predict additional ones. There have been a number of strong hints of the existence of resonances with explicitly exotic quantum numbers, which presumably represent hybrid or four-quark states. The intense kaon beams available at AGS-2000 would open up the presently inaccessible strangeonium sector of spectroscopy where many new exotic states are predicted to exist. In addition, access to this sector would allow critical measurements with the power to distinguish between currently viable theoretical approaches to explaining the observed spectrum. Many new tests of our understanding of baryon spectroscopy would also be available at AGS-2000.

b) Antiproton studies: The AGS has the potential to become the world's most intense source of low-energy antiprotons. Intense, pure, beams of cooled anti-protons could be provided in the energy range up to 5.2 GeV/c. A rich variety of studies could be carried out with such a facility. Examples include (i) a study of the reaction $\bar{p}p \rightarrow \bar{\Omega}^- \Omega^-$, which is forced to occur through complete annihilation of the initial-state quarks. This would create a very high density system of quarks and anti-quarks, where surprises could arise; (ii) a determination of the true J/ψ - nucleon cross-section by producing low-momentum J/ψs in the nucleus via $\bar{p}$ annihilation on nuclear protons; (iii) a study of direct CP-violation by comparing the decay angular distributions of Λ's and $\bar{\Lambda}$'s following $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$. An experiment of this kind can be designed to have *no* first-order systematic errors! In addition to the above, it is possible to envision a cold antiproton source with at least twenty times the intensity of what is likely to be possible at CERN. This would allow the production of large numbers of anti-hydrogen atoms, making possible many very interesting tests of CPT.

c) Exclusive scattering and polarization: An experiment has been proposed to investigate the possible relationship between three mysterious phenomena observed in large angle pp elastic scattering experiments in the incident energy range 10-12 GeV. These are: 1) anomalies in the energy dependence of the 90° cross section in this range; 2) the puzzling energy dependence of color transparency when this scattering is studied off nuclei; 3) the onset of a large spin asymmetry in this range.

d) Hypernuclei: This subject is closest to nuclear physics but needs high energy beams of the quality of the future AGS to proceed in a meaningful way. The study of nuclear systems with more than the "traditional" pair of ingredients, neutron and proton, is interesting in its own right and also a new test of some of the basic theoretical ideas of nuclear physics.

3. Heavy Ion Physics

Although most of the emphasis in AGS-2000 was on the elementary particle physics and the first priority for high energy heavy ion physics at Brookhaven is RHIC, there remains an important program of high energy heavy ion physics for the AGS. Perhaps this can be best appreciated by realizing that in terms of integrated beam time, stopping the heavy ion program at the AGS after the run in calendar 1997 is roughly analogous to having stopped the high energy program at the AGS in 1963.

The AGS has important characteristics for heavy ion physics which offer useful and important additions to the RHIC program. The "luminosity" of AGS fixed target experiments is more than 100,000 times greater than the RHIC luminosity. Thus, if a process can occur at AGS energies with comparable cross sections, there is a great advantage to studying it at the AGS. This is the case for the searches for strange quark matter, for example. In addition, it is known that AGS collisions produce a very dense hadronic medium, although with a lower temperature and greater baryon density than is expected at RHIC. It will be important to understand the behavior of the various "signatures" for the quark gluon plasma at AGS conditions in order to correctly interpret them at RHIC energies.

Other Considerations

The overriding considerations for the operation of the AGS in the next decade must, of course, be the interest and potential of the scientific program. However, once that has been established, there are other aspects of the AGS program which deserve mention. Although experiments at the AGS are of increasing sophistication, they are smaller, less expensive, and more quickly executed than experiments at newer, larger facilities. This offers important avenues for younger physicists to exhibit leadership and to exercise their creativity. Finally, we note that since the AGS must be maintained as a viable accelerator to serve as an injector to RHIC, the cost of an AGS fixed target experiment need be only the incremental cost of the experiment itself along with some modest additional operating costs. This means that AGS fixed target experiments are substantially cheaper than they would have been before the RHIC era!

Conclusions

The remainder of this document contains brief summaries of the experiments considered by the working groups in the AGS-2000 Workshop. These summaries expand on points discussed above. Clearly also they reflect the range of maturity of the development of the individual ideas. They are also different in other ways. For example, the antiproton program presents a possible new broad range of studies covering a breadth of physics from "exotic" atoms to tests of fundamental invariance principles, while the K decay experiments discuss individual rather sharply targeted (in terms of physics goals) experiments. Still others, such as the possibilities afforded by the g-2 apparatus, offer new opportunities for existing facilities. We believe that these summaries illustrate the breadth, scope, high interest and importance of the future research program of the AGS.

AGS-2000 Workshop Co-chairmen
Laurence Littenberg
Jack Sandweiss
August 23, 1996

An Experiment to measure the branching ratio $K^+ \to \pi^+\nu\bar{\nu}$

I-H.Chiang(1), J. Doornbos(2), J.Frank(1), J.Haggerty(1), S.Kettell(1), M.Kuriki(3), K.Li(1), L.Littenberg(1), N.Muramatsu(3), T.Shinkawa(4), R.Strand(1) and S.Sugimoto(3)
(1) *Brookhaven National Laboratory (BNL), Upton, NY 11973*
(2) *TRIUMF, Vancouver, B.C. V6T 2A3, Canada*
(3) *Institute for Nuclear Study (INS), University of Tokyo, Tokyo 188, Japan*
(4) *National Laboratory for High Energy Physics (KEK), Tsukuba 305, Japan*

We discuss an experiment to measure the $K^+ \to \pi^+\nu\bar{\nu}$ branching ratio to ~20%. The detector would consist of the E787 detector with some modifications.

1 Introduction

The rare decay $K^+ \to \pi^+\nu\bar{\nu}$ is a flavor changing neutral current, mediated in the standard model by heavy quark loop diagrams, and in particular, is sensitive to the CKM matrix element $|V_{td}|$. The theoretical prediction for this branching ratio is very clean: the hadronic matrix element can be determined from the $K^+ \to \pi^0 e^+\nu$ branching ratio via an isospin transformation, the long distance contributions are negligible, and the QCD corrections (next to leading order) bring the theoretical uncertainty to 7% [2].

The branching ratio as predicted by the standard model is between 0.6—3.0×10^{-10} with a most probable value of 1×10^{-10}. Over the next few years the E787 experiment at the AGS is expected to reach a single event sensitivity of a few$\times10^{-11}$ and should therefore observe $K^+ \to \pi^+\nu\bar{\nu}$. This working group studied the feasibility of a cost-effective experiment to measure the $K^+ \to \pi^+\nu\bar{\nu}$ branching ratio to < 20% on the AGS2000 time scale.

2 The E787 experiment

The results from the 1989-91 data set [1] represent a single event sensitivity of $\sim 1 \times 10^{-9}$ with an expected background level of 1×10^{-10} from $K_{\mu2}$ and 1×10^{-10} from $K_{\pi2}$. The upgrades of the experiment between 1991 and 1995 appear to have reduced the expected background levels (based on preliminary analysis on the 1995 data) to $K_{\mu 2} \sim 3 \times 10^{-12}$ and $K_{\pi 2} \sim 1 \times 10^{-11}$. Further improvements in the $K_{\pi 2}$ rejection are currently proceeding. For the typical conditions of the 1995 run: 15 Tp protons per pulse (ppp), a stopped kaon rate of KB = 1.2 M/spill, a deadtime of 25% and an online photon veto loss of 10%, E787 can expect a sensitivity of 1/3 event per year of 16 weeks of production data taking. It is expected that with further improvements E787 may reach a sensitivity of 1/2 event per year and should see ~ 2–3 events by 1999 (assuming no non-Standard Model physics). The rate dependence of the acceptance has been measured from the 1995 data. Approximately 50% of the incident kaons for which the detector was live are lost. From the 1996 data we have seen that this rate dependent acceptance loss is proportional to the incident flux at the upstream end of the detector. This rather large rate dependent loss implies that E787 will not be able to gain much sensitivity by simply increasing the kaon flux without further improvements to the detector..

3 A new experiment

In the following discussion, the experience and lessons learned from E787 provide the foundation for a new experiment. The experiment is based upon the techniques and technology of E787 because the extensive measurements and analysis of E787 provide a high level of confidence in projecting a new experiment to the required sensitivity. The level of background rejection achieved by E787 is sufficient for a relatively clean and convincing measurement of $K^+ \to \pi^+ \nu\bar{\nu}$. The primary requirement is to stop more K^+ near the center of the detector. Most of the improvements call upon the AGS and beam line to provide more stopping kaons and the trigger and DAQ to process the increase with no additional deadtime; modest upgrades to the E787 detector are also envisioned. These improvements, for the most part, entail no increase in incident kaons.

1. Many of the acceptance losses suffered by E787 are proportional to the incident flux of particles (K^+ or π^+) entering the detector. A significant reduction in the incident flux was achieved when the LESBI beam line was upgraded to the LESB3 beam line in 1992. This beam improved the number of K^+ per targeted proton, and also improved the K^+:π^+ ratio from about 1:3 to 3:1. Thus the kaon flux was increased by a factor of three with no additional losses in acceptance.

   The most important factor remaining that we wish to exploit in this new experiment is to improve the fraction of incident K^+ that come to rest near the center of the apparatus. We find that only 1/6 of the K^+ being transported at 790 MeV/c incident on our detector can be brought to rest in the kaon stopping target. Most of the rest interact or scatter in the degrader just upstream of the stopping target, and cause accidentals that cause acceptance losses. By removing some of the degrader and transporting a lower momentum K^+ beam, the fraction of the incident kaons stopping in the target increases. The increase in sensitivity is directly proportional to the increase in the stopping fraction. During the 1995 run E787 ran at 790 MeV/c; during the 1996 run the momentum was lowered to 730 MeV/c and 710 MeV/c. For a new experiment, we propose to lower the momentum to < 600 MeV/c. At 600(550) MeV/c we expect an increase of sensitivity of ×1.7(2.0) compared to 790 MeV/c. A design for a 600 MeV/c beamline was discussed wherein the number of incident kaons per proton is not reduced with respect to the present LESB3 beamline. An alternative to this new beamline would be to increase the number of protons on target by ×1.9(2.7) at 600(550) MeV/c, using LESB3. By making modest changes to the last quadrupoles and Cerenkov counter, thereby allowing LESB3 to be shortened, the number of protons on target may need to be increased by only a factor of 1.4(1.9).

2. Increase the spill length. Currently we run with a 1.6 sec spill every 3.6 sec (40% duty factor); in the AGS2000 era, with an accumulator, the inter-spill period can be reduced to 1 sec. The direct increase in sensitivity with the accumulator is $\frac{1.6/2.6}{1.6/3.6} = 1.4$. This requires no additional protons per pulse (ppp). If an accumulator is not built we could increase the duty factor by compensating with additional protons. By increasing the spill length to 3.2 sec (62% Duty Factor) we can increase our sensitivity per hour by ×1.4, while requiring ×2 more protons. These would keep the instantaneous rates and acceptance constant, but increase the sensitivity (KB/hour).

3. Bunched beam. The general idea of using a bunched beam would be to reduce the rates in the detector at the time the kaon decays ("π time") and perhaps also at the time the pion decays, by increasing rate at the time the incident kaons arrive. Currently the detector is live for K decays up to 60ns (and for π decays for up to an additional 80ns), so we need the RF period to be larger than 60ns (up to 140ns). The time of flight difference between K^+'s and π^+'s is ~20ns, so we actually need the RF period to be larger than 80ns. For a stopped kaon rate (KB) that is ×4 that of E787 (KB = 4 MHz), we could consider bunched beam with a 10 MHz frequency. At an RF frequency of 10 MHz, we would have an average of 0.4 K/bucket and a 80ns period with no additional beam particles. The probability of more than one stopped kaon per pulse compared to exactly one is less than 25%. E787 has taken some data to quantify the potential improvements

from a bunched beam. If, by means of a bunched beam, the rates in the detector elements at π time can be reduced by $\times 2$ per incident K, the proton flux could be increased by $\times 2$ with little or no acceptance loss. In this case the sensitivity increase would be $\times 2$.

4. Take advantage of the increased running time in the RHIC era. If RHIC runs for 40 weeks/year and we assume 90% of this time is available for SEB; we will have $\times 2$ more running per year (36 weeks vs. 18 weeks in pre-AGS2000 era).

5. Increased flux. All previous assumptions have kept the instantaneous flux constant. With modest improvements to the online RS photon veto, additional demultiplexing of the TD's, and further detector upgrades it may be possible to increase the incident flux by $\sim \times 2$ with little loss in acceptance and little loss in background rejection.

As a conservative approach we assume that the combined improvements from points 3) and 5) above give an increase in sensitivity of $\times 2$ (instead of $\times 4$). The net increase in sensitivity per year from these improvements is 1.7 $\times 1.4 \times 2 \times 2 = \times 10$. In order to achieve this increase we need an increase in the number of protons on target by $1.4 \times 2 \times 2 = \times 5.6 = 85$ Tp. This would lead to an expected $\sim$3 events per year.

3.1 Cost

A summary of the estimated cost of capital equipment is shown in Table 1. The sensitivity improvement and additional protons needed are also shown for each of the proposed improvements. This table assumes that the momentum will be lowered to 600 MeV/c and that the beamline shortened by $\sim$2m. It assumes that the AGS Accumulator is not built, but the spill length and cycle time are increased to 3.2 sec and 5.2 sec, respectively. It also assumes that a combined factor of two increase in sensitivity is achieved by bunching the beam and/or running at higher instantaneous rates.

4 Conclusion

We believe that the goal of making a significant measurement of $|V_{td}|$ is quite exciting, since it would allow the CKM model of CP violation to be critically tested. Such a measurement can be accomplished via a determination of the branching ratio for the rare decay $K^+ \to \pi^+ \nu\bar{\nu}$ based on $\sim$ 10–20 events with an expected background level of $< 10\%$ of the signal. Though this can not be done by the present AGS, LESB3, or E787 detector, we expect that realistic improvements in all these components can be achieved in the AGS2000 era. We require several years of 40 week runs of SEB during the RHIC era with

action	Sens./yr.	ppp	cost
lower p(short beam)	×1.7	×1.4	$200k
duty factor	×1.4	×2.0	–
longer runs	×2	×1	–
bunched beam	×2	×2	$1–500k
trigger/DAQ mods			$400k
detector mods			$400k
total	×9.5	×5.6 (85Tp)	$1500k

Table 1: Proposed increases in sensitivity per year with associated increases in protons on target and estimated cost of capital equipment. Increases in sensitivity are compared to 1995.

80TP on target, a modestly shortened LESB3 line, an increased AGS duty factor, and significant, but currently achievable improvements in the E787 detector and DAQ systems. We expect that the total cost for the required modifications to the LESB3 line and the E787 detector and DAQ will be under $1500k. We note that on the same timescale far greater resources are being expended to extract equivalent information from the B system.

5 References

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Detecting the Decay $K_L \to \pi^0 \nu \bar{\nu}$ at the AGS "Instant" Report of the $K_L \to \pi^0 \nu \bar{\nu}$ Working Group

AGS-2000 Working Group

G. Bunce, W. Glenn, L. Littenberg, C. Woody

Brookhaven National Laboratory

M. Ito

Continuous Electron Beam Accelerator Facility,

G. Bock, G. Buchalla

FNAL

H. Kurashige, N. Sasao

Kyoto University

D. Bryman, A. Konaka, J. Macdonald,T. Numao, R. Poutissou

TRIUMF,

G. Thomson

Rutgers University

M. Hebert

Stanford University

M. Blecher, D. Gibaut, K. Gotow, K. Kinoshita

Physics Department, Virginia Polytechnic Institute

May 17, 1996

1 $K_L \to \pi^0 \nu\bar{\nu}$ – Theoretical Motivation

Understanding the phenomenology of quark mixing and CP violation is currently one of the central goals of particle physics. Testing the CKM ansatz of the Standard Model through precise determination of its basic parameters, several of which are poorly known at present, is crucial. To assure a clear interpretation of experimental results, the ideal observable must not only be sensitive to the fundamental parameters of interest, but must also be calculable with small theoretical ambiguity.

The rare decay $K_L \to \pi^0 \nu\bar{\nu}$ is uniquely suited for this purpose; it is entirely governed by short-distance physics involving the top quark making uncertainties extremely small. The hadronic matrix element can be extracted from the well measured decay $K^+ \to \pi^0 e^+ \nu$, where small isospin breaking effects have been calculated. The dominant uncertainty due to renormalization scale dependence can be practically eliminated once next-to-leading QCD corrections are included. The theoretical uncertainty for $B(K_L \to \pi^0 \nu\bar{\nu})$ is thereby reduced to the 1% level. At the same time, $K_L \to \pi^0 \nu\bar{\nu}$ is driven by direct CP violation and thus of great interest. Its branching ratio is a clean measure of the Wolfenstein parameter η the height of the unitarity triangle.

The charged mode $K^+ \to \pi^+ \nu\bar{\nu}$ is closely related to $K_L \to \pi^0 \nu\bar{\nu}$, except that it is not CP violating and receives a non-negligible charm contribution. As a consequence the theoretical uncertainty is slightly higher, about 5% for the branching ratio, but still very small. $B(K^+ \to \pi^+ \nu\bar{\nu})$ allows the extraction of $|V_{td}|$. Together with $B(K_L \to \pi^0 \nu\bar{\nu})$ the unitarity triangle is completely determined as illustrated in Fig. ??. Only a few other potential observables, like x_s/x_d, $B \to l^+ l^-$ or certain CP asymmetries in B decays, have a comparable potential.

The decay modes $K \to \pi \nu\bar{\nu}$ probe the weak interaction sector of the Standard Model at the quantum level and are sensitive to the physics at very short distance scales, especially to the top-quark and its weak couplings. In addition they are exceptionally clean from a theoretical point of view, the neutral mode in particular. They provide therefore an excellent and unique opportunity for significant progress in our understanding of flavordynamics and CP violation.

A measurement of $K_L \to \pi^0 \nu\bar{\nu}$ in the expected SM range about 3×10^{-11} would unambiguously establish the SM origin of CP violation and determine the SM CP-violation parameter η with unrivaled precision. Absence of of

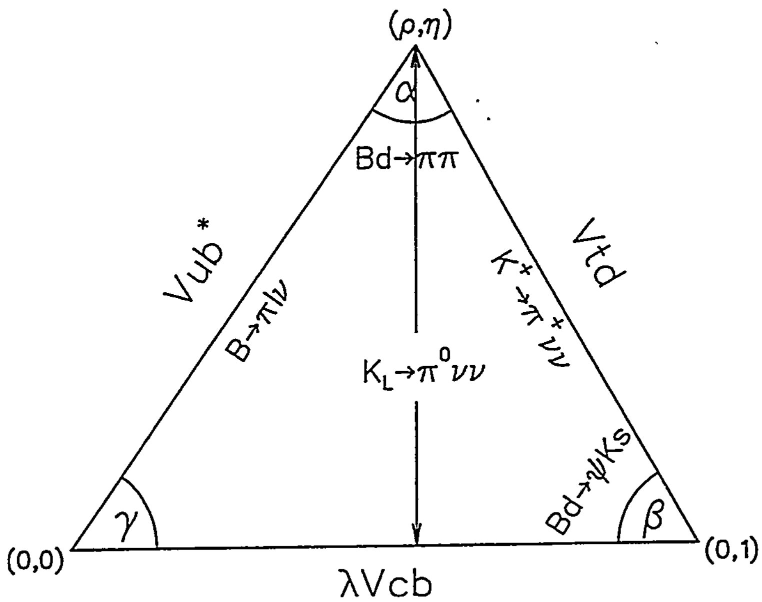

Figure 1: The unitarity triangle.

$K_L \to \pi^0\nu\bar{\nu}$ would certainly indicate new physics. Along with the anticipated measurement of $K^+ \to \pi^+\nu\bar{\nu}$, the CKM triangle would be completely specified in a manner entirely complementary to the studies to be done at the B factories.

2 Concept of the $K_L \to \pi^0\nu\bar{\nu}$ Experiment

The goal of this experiment is the observation and study of the CP violating decay $K_L \to \pi^0\nu\bar{\nu}$ if it occurs within the SM range. In order to definitively observe $K_L \to \pi^0\nu\bar{\nu}$ in the presence of potentially overwhelming backgrounds (in particular, the CP-violating decay $K_L \to \pi^0\pi^0$ ($K_{\pi 2}$) which occurs at a branching ratio of 9×10^{-4}) we have chosen a method which maximizes the information available. The K_L momentum will be determined on an event-by-event basis using time-of-flight – a technique only recently feasible at the AGS due to the development of a micro-bunched slow extracted beam. In addition , the π^0 from the $K_L \to \pi^0\nu\bar{\nu}$ will be fully reconstructed by measuring the diections and energies of each decay photon giving the K_L

decay time and position and allowing a large fraction of the phase space to be accessed. The two-body $K_{\pi 2}$background can then be identified by the unique momentum of the π^0 when viewed in the K_L rest frame.

The use of an intense low energy neutral K beam suitable for time-of-flight measurements also facilitates the suppression of other backgrounds. For example, neutron interactions which produce π^0's in the decay region can be suppressed since beam neutrons mostly arrive later than the K's of interest and are largely below the π production threshold. Lambda decays ($\Lambda \rightarrow n\pi^0$), a serious potential background source at higher energies, are suppressed to negligible levels. In addition, all photons from the production target region arrive simulataneously, several ns prior to the fastest K's of interest.

In recent years the AGS has achieved new records of intensity opening up new opportunities for studies of rare processes. The present peak (slow) extraction current of 6×10^{13} protons/pulse (with 1 s pulses every 3 s) is expected to double by 1999. For estimates here we will assume that 6×10^{13} protons/pulse will be available for K_L production. Coupled with a high current micro-bunched beam, good duty factor and extended availability during the RHIC era,[1] the AGS is potentially the ideal accelerator site for ultra-rare neutral kaon decay experiments employing time-of-flight.

The concept of the experiment is shown in Fig. ??. The 24 GeV beam, bunched in 130 ps wide buckets spaced by 50 ns, strikes a Pt target. The 500 μsr solid angle neutral beam is extracted at a production angle of 45 degrees to produce a K_L beam with momentum 0.75 ± 0.7 GeV/c and a flux of approximately 2×10^8 per pulse at 10 m from the target. Using low momentum enhances the time-of-flight resolution achievable. Downstream of the final beam collimator is a 5 m long decay region which is followed by the main detector. Approximately 15% of the kaons decay yielding a rate of 3×10^7 per pulse. The beam region is evacuated to a level of 10^{-7} Torr to suppress neutron induced π^0 production in the beam. The decay region is surrounded by photon veto detector.

In the forward detection region a high-quality, fully-active photon detector consists of a pre-radiator followed by a fine-grained 12 radiation length

[1]RHIC is expected to operate for 30 to 40 weeks per year and requires injection from the AGS for approximately 2 hours/day. Thus, approxomately 22 hrs./day are available for AGS proton operation.

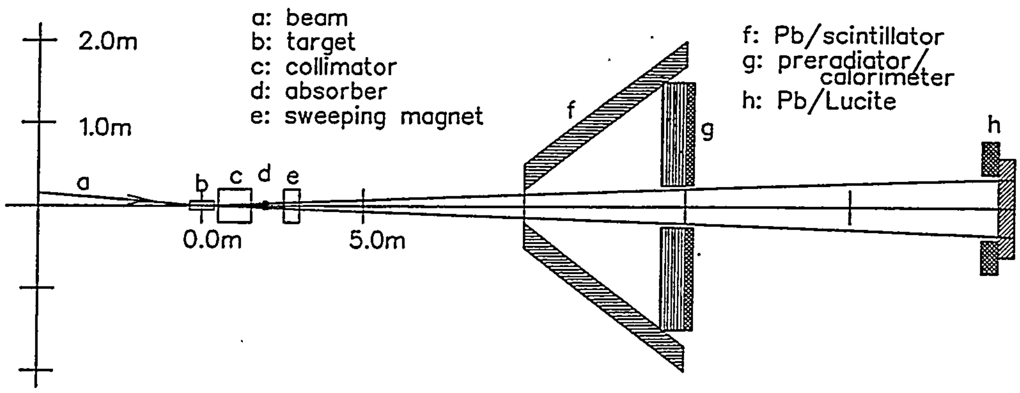

Figure 2: Conceptual detector design.

barium fluoride (BaF_2) crystal calorimeter. The pre-radiator measures the photon positions and directions accurately in order to allow reconstruction of the K_L decay vertex, which in turn is necessary for the K_L momentum measurement via time-of-flight. In the initial design, the pre-radiator has a total thickness of two radiation lengths and consists of alternating layers of 2 cm thick plastic scintillator and dual coordinate drift chambers. Outside a central fiducial region, Pb will be placed between the preradiator scintillator elements so that the perifery of the preradiator also functions as a photon veto insuring nearly complete 4π sr coverage with high quality photon detectors. Downstream of the main π^0 detector, a beam hole photon counter is made from Čerenkov detectors insensitive to neutrons.

A trigger will be based on the appearance of two photon clusters in the endcap detector with appropriate spatial and energy correlation and the absence of energy (above a few MeV threshold) detected elsewhere in the detector in prompt coincidence. Signals from all phototubes will be acquired using 500 MHz high speed pipeline transient digitizers (using GaAs CCD's and flash ADC's as in E787); this technique will facilitate achieving maximum timing resolution, reduction of the signal timing window and rejection of coincident pile-up backgound.

3 Sensitivity

Initial estimates (concentrated on $K_{\pi 2}$) indicate that backgrounds can be suppressed to an order of magnitude below the expected level for $K_L \rightarrow \pi^0 \nu \bar{\nu}$. The effects of the accidental background from low energy neutrons and photons, from multiple K decays and other rare K decays are being studied but appear manageable. The expected number of events for the $K_L \rightarrow \pi^0 \nu \bar{\nu}$ signal at a branching ratio of 3×10^{-11} is 80. Thus, the height of the unitarity triangle would be determined to a precision of approximately 10%. The ultimate single event sensitivity of the experiment would be approximately 2×10^{-12} limited by background.

Muon Polarization Working Group Report

Robert Adair[1], Grigor Atoyan[2], Basem Barakat[3], Milind V. Diwan[4], Jun Imazato[5], Vladimir Issakov[2], Yoshitaka Kuno[5], Thaddeus Kycia[4], Richard Larsen[1], Lawrence Leipuner[4], Hong Ma[4], Andrei Poblaguev[2], Jack Ritchie[6]

(1) Yale University, New Haven, Connecticut
(2) Institute for Nuclear Research, Moscow, Russia
(3) Louisiana Tech University, Ruston, Louisiana
(4) Brookhaven National Laboratory, Upton, New York
(5) KEK, National Laboratory for High Energy Physics, Japan
(6) University of Texas, Austin, Texas

Abstract

We have examined the physics and the experimental feasibility at the AGS of various kaon decay processes in which the polarization of a muon in the final state is measured. Valuable information on CP violation, the CKM matrix or new physics can be obtained with these measurements and therefore they are well motivated. In particular, models of non-standard CP violation that produce the baryon asymmetry of the universe could also produce effects observable in these measurements. Limits from measurements such as the neutron and electron electric dipole moment, and $\frac{\epsilon'}{\epsilon}$ in neutral kaon decays do not eliminate all of these models. We have made a more detailed examination of the measurement of the out of the plane muon polarization in $K^+ \rightarrow \mu^+\pi^0\nu$ decays. With our current knowledge of the AGS kaon beams and detector techniques it is possible to measure this polarization with an error approaching $\sim 10^{-4}$. Such an experiment would be well justified since the sensitivity is well beyond the current direct experimental limit (5.3×10^{-3}) and the projected sensitivity ($< 10^{-3}$) of the currently running experiment at KEK in Japan.

Introduction

We have examined the possibility of measuring various muon decay asymmetries that are sensitive to P, T or CP symmetries; these are tabulated in Table 1. Experimentally, CP violation has only been observed in the neutral kaon system so far. Although a theoretical description of the CP-violation in the neutral kaon system exists through the complex phase in the Standard Model CKM matrix, part or all of these phases could be consequences of deeper

	Decay	Correlations	Symmetries tested
(1)	$K^+ \to \pi^0\mu^+\nu$	$\vec{s}_\mu \cdot (\vec{p}_\mu \times \vec{p}_\pi)$	T
(2)	$K^+ \to \mu^+\nu\gamma$	$\vec{s}_\mu \cdot (\vec{p}_\mu \times \vec{p}_\gamma)$	T
(3)	$K_L \to \mu^+\mu^-$	$\vec{s}_\mu \cdot \vec{p}_\mu$	P, CP
(4)	$K^+ \to \pi^+\mu^+\mu^-$	$\vec{s}_\mu \cdot \vec{p}_\mu$	P
(5)		$\vec{s}_\mu \cdot (\vec{p}_{\mu^+} \times \vec{p}_{\mu^-})$	T
(6)		$(\vec{s}_\mu \cdot \vec{p}_\mu)\vec{s}_\mu \cdot (\vec{p}_{\mu^+} \times \vec{p}_{\mu^-})$	P, T

Table 1: *The decay modes and the polarization asymmetries or correlations of interest.*

causes that have so far eluded experiments. Over the last decade experiments at FNAL and CERN directed towards the measurement of the direct $K_L^0 \to \pi\pi$ transition or $\frac{\epsilon'}{\epsilon}$ have been inconclusive in revealing the true nature of CP-violation. Over the next decade ambitious efforts towards understanding CP-violation and the CKM matrix elements are planned with new $\frac{\epsilon'}{\epsilon}$ experiments and B-factories. The importance of these efforts is undeniable, yet it must also be important to investigate the possibility that some or all of the CP-violation comes from effects outside the minimal Standard Model, particularly the CKM matrix.

The CPT invariance of local quantum field theories requires that CP violation is equivalent to T-violation. Therefore, it would be particularly interesting to look for direct violation of T-invariance outside the neutral kaon system.

It should also be noted that CP-violation is required to generate the observed baryon asymmetry of the universe, and it is now accepted that the CP-violation embodied in the CKM matrix does not have sufficient strength for this purpose [1]. Physics beyond the Standard Model that could generate the baryon asymmetry can also generate CP or T violating muon polarizations in the kaon decay modes in Table 1.

$K^+ \to \pi^0\mu^+\nu$

The transverse or out of plane muon polarization in this decay has recently been analyzed by many authors [2, 3, 23]. The out of plane polarization is expected to be zero to first order in the Standard Model because of the absence of the CKM phase in the decay amplitude. It has been shown that any arbitrary models involving effective V or A interactions cannot produce

Asym.	Mode	Branch. Fraction	Standard Model	Final State Int.	Non-SM value	Ref.
(1)	$K^+ \to \pi^0 \mu^+ \nu$	0.032	0.0	$\sim 10^{-6}$	$\leq 10^{-3}$	[2]
(2)	$K^+ \to \mu^+ \nu \gamma$	5×10^{-3}	0.0	$\sim 10^{-3}$	$\leq 10^{-3}$	[14]
(3)	$K_L \to \mu^+ \mu^-$	7×10^{-9}	$\sim 10^{-4}$	0.0	$\leq 10^{-2}$	[17, 18]
(4)	$K^+ \to \pi^+ \mu^+ \mu -$	5×10^{-8}	$\sim 10^{-2}$	–	–	[21 –27]
(5)			0.0	$\sim 10^{-3}$	$\sim 10^{-3}$	[28,23]
(6)			$\sim 6 \times 10^{-2}$	~ 0.0	~ 0.1	[28,23]

Table 2: *The decay modes and asymmetries discussed by the working group. The rest of the columns are: the known branching ratio, the estimated Standard Model value, the value due to final state interactions, the maximum possible value allowed by non-standard physics, and the theoretical reference.*

this type of polarization. Therefore, the existence of a non-zero value of this polarization will be a definite signature of new physics beyond these models. In particular, some multi-Higgs and leptoquark models could produce such a polarization. In multi-Higgs models a charged Higgs particle mediates an effective scalar interaction that interferes with the Standard Model decay amplitude; in such models the polarization could be as large as 10^{-3} without conflicting with other experimental constraints including the measurements of the neutron electric dipole moment and the branching fraction for $B \to X\tau\nu$, or $b \to s\gamma$ [4-5]. Irreducible backgrounds, i.e., final state interactions (FSI), to the out of plane polarization in this decay are expected to be small ($\sim 10^{-6}$) and therefore can be ignored [6].

The best previous experimental limits were obtained almost 15 years ago with both neutral [7] and charged kaons [8] at the BNL-AGS. The experiment with K^+ decays produced a measurement of the transverse polarization, $P_\mu^T = 0.0031 \pm 0.0053$. The combination of both experiments could be interpreted as a limit on the imaginary part of the ratio of the hadron form factors, $Im\xi = Im(f_-/f_+) = -0.01 \pm 0.019$. This limit is mostly independent of theoretical models and the experimental acceptance. By using the approximate formula, $P_\mu^T \approx 0.183 \times Im\xi$, one may reinterpret the above measure of $Im\xi$ as a combined limit on the polarization, $P_\mu^T \approx -0.00185 \pm 0.0036$. This 1980 era measurement was based on 1.2×10^7 K_L^0 and 2.1×10^7 K^+ decays to $\mu^+\pi\nu$ and was limited by statistics and backgrounds.

Currently an experiment is in progress at the KEK-PS, E246 [9], to measure P_μ^T with a new technique of using a stopping K^+ beam and measuring the muon decay direction witl spin precession. They expect to reach a sensitivity of 9×10^{-4} ($Im\xi < 4\times10^{-3}$) with $1.8\times$ events. The experiment will try to minimize systematics by using the cylindrical symm of the apparatus and by using the backward-forward π^0 symmetries of the decay at rest. ' disadvantage of the stopping technique, however, is the low K^+ stopping rate. Neverthel the results of this experiment will be very valuable to future experiments.

A new experiment has been designed at the BNL-AGS to perform this measurem with an error on the polarization approaching 10^{-4} [11]. The design is based on the 1 experiment. The main improvement in the experiment will be the 2 GeV/c separated char kaon beam decaying in flight. The separated beam will reduce background counting ra in the detector per accepted event. The other improvements will be higher acceptance a analyzing power with a larger apparatus and a more finely divided polarimeter. Unlike 1980 design the apparatus will also have better overall event reconstruction using track chambers and the larger calorimeter. There is a possibility of improving the polarime design significantly using liquid scintillator mixtures that retain muon polarization [12]. T experiment will collect approximately 550 events per AGS pulse per 3.6 seconds. Thus statistical accuracy of the polarization measurement in a 2000 hr (2×10^6 pulses) run will

$$\delta P_T \approx \frac{1.20^{\frac{1}{2}}2^{\frac{1}{2}}}{0.35(2\times10^6\cdot550)^{\frac{1}{2}}} \approx 1.3\times10^{-4}$$

where $\sqrt{1}.2$, $\sqrt{2}$, 0.35, are dilution factors in the analyzing power due to backgrounds, t precession magnetic field, and the muon decay, respectively. The sensitivity to $Im\xi$ is giv by

$$\delta Im\xi \approx \delta P_T/0.2 \approx 7\times10^{-4}$$

where 0.2 is a kinematic factor that includes the acceptance in the Dalitz plot and t orientation of the decay in the center of mass. With such high statistical power, systema issues will become the main concern. The cylindrical symmetry of the apparatus and t precession technique (see [8]) will cancel most systematic errors to first order. Neverthele the second order systematics will require some new techniques. The experiment will collect large sample of data including $K^+\to\mu^+\nu$, $K^+\to\pi^+\pi^0$, and $K^+\to\pi^0\mu\nu$ events in differe parts of the decay phase space. The muon decay asymmetries from these various ensembl of events can be measured to understand the detector systematics to very high accuracy.

$K^+ \to \mu^+ \nu \gamma$

The T violating out of plane polarization of the muon in this decay is related to the same in $K^+ \to \pi^0 \mu^+ \nu$ decay. The former can be caused by an effective pseudo-scalar interaction, while the latter by an effective scalar interaction. Therefore searches for T violation in both decay modes are complementary [14]. The T violating polarization could be $\sim 10^{-3}$ without violating other experimental bounds. It is estimated [15] that the electro-magnetic FSI for this interaction can induce an out of plane muon polarization of the same order of magnitude. An accurate theoretical calculation will be needed to subtract the FSI from any observation. On the other hand, this FSI induced effect could be considered a useful calibration point for the apparatus that will also be used for the new $K^+ \to \pi^0 \mu^+ \nu$ experiment.

The proposed new experiment is optimized to study muon polarization in $K^+ \to \mu^+ \pi^0 \nu$ decays. Nevertheless, we have investigated the feasibility of measuring T-violation in $K^+ \to \mu^+ \nu \gamma$. The event selection and analysis of $K^+ \to \mu^+ \nu \gamma$ will be very similar to $K^+ \to \mu^+ \pi^0 \nu$ events except that events containing more than 1 photon will be vetoed to reject background from $K^+ \to \mu^+ \pi^0 \nu$, $K^+ \to \pi^+ \pi^0$, and $K^+ \to \pi^+ \pi^0 \pi^0$ events. Further background rejection will be achieved by matching the measured muon range in the polarimeter with the muon energy from a constrained fit to the photon momentum, the muon direction, and the known kaon momentum. We expect to collect ~ 100 events per AGS pulse. However, the signal to background ratio with out current design will be about 0.3, making it difficult to reach sensitivities of 0.001 for the polarization. Two improvements to the detector will reduce the backgrounds further: If the decay volume can be surrounded by photon veto counters with a veto threshold of 10 MeV to detect the low energy photons from π^0 decays, the background level can be reduced to about 10%. Secondly, if the calorimeter resolution can be improved (we have assumed $\sigma(E)/E \sim 8\%/\sqrt{E}$) then the muon range match can be made narrower, thus separating the signal and background better.

$K_L \to \mu^+ \mu^-$

The longitudinal muon polarization in this decay violates CP invariance. This decay amplitude is known to be dominated by the two photon intermediate state. Interference of this amplitude with some other flavor changing neutral scalar interaction could produce a non-zero longitudinal polarization. Within the Standard Model such an interaction could take place through second order loop diagrams involving the Higgs particle. However, direct constraints on the top quark and Higgs masses make the value of the polarization within the Standard Model quite small, $|P_L(K_L \to \mu^+\mu^-)| \sim 7 \times 10^{-4}$ [17]. Such a polarization could also arise in non-standard models that introduce new flavor changing neutral scalars. For example, Wolfenstein and Liu [18] have suggested that in two Higgs doublet models such a polarization could be as large as 0.10 without violating the bounds from the neutron electric dipole moment, $m_{K_L} - m_{K_S}$, ϵ, and ϵ'.

The main experimental difficulty in this measurement is the small branching fraction of the decay, 7×10^{-9}. Therefore much effort must be put into separating these events from background before polarization analysis can be performed. Experiment E871 [19] has collected the largest number of these events so far; they expect to have ~ 10000 events at the end of the 1996 running period with little background. The experiment is optimized to look for $K_L \to \mu^\pm e^\mp$. We have made a rough estimate that if the experiment were optimized for $K_L \to \mu^+\mu^-$ and the beam intensity were increased E871 could collect about 20000 events in two years of running. With appropriate upgrades to the marble muon range detector will allow approximately 50% of the muon decays to be analyzed. Y. Kuno has suggested that a polarimeter made with liquid scintillator could help this measurement by improving the analyzing power and lowering the cost of the polarimeter. Thus aside from kinematic factors the polarization could be measured with the following error:

$$\delta P \approx \frac{\sqrt{2}}{0.3\sqrt{10000}} \approx 0.05 \qquad (1)$$

where $\sqrt{2}$ and 0.3 are factors due to the precession magnetic field in the polarimeter and the muon decay analyzing power, respectively. We have not calculated the kinematic dilution factors that could arise from the orientation of the decay in the center of mass of the kaon.

$K^+ \to \pi^+\mu^+\mu^-$

This decay has recently been experimentally observed and measured to have the branching ratio of 5×10^{-8} [20]. The decay has a very rich structure which could lead to important measurements: Table 1 shows three different asymmetries that could be interesting to measure. The decay has recently been analyzed quite extensively [21–28]. The several different processes that govern the decay are as follows: one photon intermediate state, two photon intermediate state, short distance graphs of "Z-penguin" and "W-box", and potential contributions from extensions to the Higgs sector. The interference of these graphs leads to various polarization effects. Although the theoretical analysis in the literature does not seem to be complete – in particular, strong interaction corrections and electro-magnetic final state effects – there is a consensus on the following:

The CP conserving longitudinal polarization (asymmetry (4) from Table 1) of the μ^+ is sensitive to the Standard Model Wolfenstein parameter ρ. The value of this polarization within the Standard Model is estimated to be ~ 0.01 and depends on the experimentally accepted phase space region. There is a small but non-negligible contribution to this polarization from the long distance 2 photon graph which cannot be calculated accurately at this time.

The T violating out of plane polarization (asymmetry (5) in Table 1) is expected to be very small within the Standard Model and the final state interaction correction to this polarization is expected to $\sim 10^{-3}$. T violating spin correlations that involve both μ^+ and μ^- polarizations (asymmetry (6)) are expected to have much smaller final state interaction corrections and are theoretically clean. Such asymmetries have substantial T violating contributions from the CKM matrix; they are expected to be ~ 0.06 in some parts of the decay phase space. A good measurement would be sensitive to both the top quark mass and the CKM parameter η. It could also be sensitive to non-standard model physics in the same manner as $K_L \to \mu^+\mu^-$.

Once again the main experimental difficulty will be in selecting the rare $K^+ \to \pi^+\mu^+\mu^-$ decays from background. The main background is $K^+ \to \pi^+\pi^+\pi^-$ decays in which the charged pions are misidentified as muons. This background must be suppressed in the trigger and the analysis. Experiment E865 [29] at the AGS is currently the best apparatus to perform this measurement. The experiment is, however, optimized for a search for $K^+ \to \pi^+\mu^+e^-$, and therefore will require some reconfiguration. In particular, the muon range finder will have to be changed to stop more muons and analyze the polarization. A rough estimate of the sensitivity can be made based on the number of K^+ in the decay region of the experiment, $\sim 10^7$ per AGS spill per 3.6 sec, the geometric acceptance for $K^+ \to \pi^+\mu^+\mu^-$, 0.1, and the efficiency for muon decay detection of about 0.5. The longitudinal polarization could be measured in a 2000 hr run (2×10^6 spills) with an error of about:

$$\delta P_L \approx \frac{\sqrt{2}}{0.3(2\times 10^6 \cdot 10^7 \cdot 5\times 10^{-8} \cdot 0.1 \cdot 0.5)^{\frac{1}{2}}} \approx 0.02 \qquad (2)$$

where $\sqrt{2}$ and 0.3 are factors due to the precession magnetic field, and the muon decay analyzing power, respectively. Clearly, measuring asymmetries that require analyzing both μ^+ and μ^- polarizations will be very difficult with current technology since μ^- decays have a much lower analyzing power due to muon capture into atomic orbits around nuclei in the polarimeter.

Table 1 contains a summary of the various polarization asymmetries discussed b working group. Table 2 contains the approximate estimated values of the asymmetries w the Standard Model and outside the Standard Model. Some of the numbers from the va references have been adjusted to account for the new knowledge of the top quark mass GeV/c^2). In the case of $K_L \to \mu^+\mu^-$ and $K^+ \to \pi^+\mu^+\mu^-$ the theoretical estimates fo maximum possible non-standard contributions to T violation do not agree; here the r value of various estimates is chosen.

Conclusion

Muon polarization from kaon decays have a rich phenomenology. In the case of $K_L \to \mu$ and $K^+ \to \pi^+\mu^+\mu^-$ new measurements could lead to important constraints on the Stan Model CKM parameters, in particular the Wolfenstein parameters ρ and η. It is, howe difficult to reach the level of sensitivity needed to measure these parameters well with cur technology. Nevertheless, the experimental difficulties should be compared to the difficu facing the rare kaon decay measurement of $K_L \to \pi^0\nu\bar{\nu}$, which is sensitive to the same phy

As shown in Tables 1 and 2 for many cases limits on the muon polarization will pr new physics beyond the Standard Model. In particular, the polarization will be sensitiv the physics of a more complicated Higgs sector or leptoquarks that could give rise to or T violation outside the Standard Model. The other source of CP violation needed baryogenesis could be the motivation for such searches.

We have examined the measurement of the out of plane muon polarization in K^+ $\mu^+\pi^0\nu$ decays in more detail. Such a measurement will not be sensitive to the Stand Model CP violation physics. Nevertheless, the measurement can be performed with sensiti approaching $\delta P \sim 10^{-4}$, which is well beyond both the current direct limit of $\sim 5.3 \times 1($ and indirect limit of $\sim 10^{-3}$ from other experimental constraints. Although the electric dip moments of the neutron and electron are considered more favorably for T violation outs the Standard Model they do not cover the entire spectrum of models. At the moment i measurement of T violating polarization in $K^+ \to \mu^+\pi^0\nu$ decays is well justified and sho be considered complementary to other efforts in understanding CP violation.

We would like to thank Bill Marciano, Robert Garisto, Lawrence Littenberg, Steve Adl Amarjit Soni for useful discussions.

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Report of the Charged K Decay in Flight Working Group
AGS 2000

Steven Adler, Keith Baker, Andre Poblaguev, Michael Zeller

1 Introduction

The charged K decay in flight working group studied possibilities of new or improved experiments looking at decays of K mesons in an in flight environment. At present E865 can examine about 10^7 K^+ decays per machine pulse, which can yield typically thousands of events of the types:

Mode	B.R.
$\pi^+\pi^-e^+\nu$	4×10^{-5}
$\pi^+e^+e^-$	3×10^{-7}
$\mu^+\nu e^+e^-$	10^{-6}
$\pi^+\pi^0e^+e^-$	$\sim 10^{-8}$
$e^+\nu e^+e^-$	2×10^{-7}
$\pi^+\mu^+\mu^-$	5×10^{-8}

One can also observe as many as 10^{10} events resulting from K^+ and K^- decays to $\pi^+\pi^+\pi^-$ and $\pi^-\pi^-\pi^+$, respectively.

Some of the physics that can be studied with such decay modes are the electromagnetic and weak structure of charged K mesons, Chiral Perturbation models, the $\pi\pi$ interaction, and CP violation outside of the K^0 sector.

The study group examined some of these, and other modes, to see if a program in this area could extend into the AGS 2000 era.

2 Several possible experiments

2.1 Polarization in $K^+ \to \pi^+\mu^+\mu^-$

Addition of a polarimeter to the E865 apparatus would enable analysis of the polarization of the muons in this decay. Such a polarimeter might consist of about 120 modules of proportional chambers and 3mm thick aluminum plates which would be able to stop approximately 80% of the muons from these decays. The in flight environment for these decays is superior to that at rest both because of the opportunity for higher statistics and larger acceptance over the Dalitz plot. It is possible to collect as many as 50,000 events of this mode which would permit a measurement of the μ^+ polarization to a precision of a few percent. Since only a few $\pi\mu\mu$ events have even been observed thus far, this configuration with this many events seems at first blush to present a significant opportunity.

There are several correlations that can be measured that are sensitive to violations of discrete symmetries, *e.g.* (1) $\vec{s}_{\mu^+} \cdot (\vec{p}_{\mu^-} \times \vec{p}_\pi)$, (2) $\vec{p}_\pi \cdot (\vec{s}_{\mu^+} \times \vec{s}_{\mu^-})$, (3) $(\vec{s}_{\mu^+} \cdot \vec{p}_{\mu^+})\vec{s}_{\mu^-} \cdot (\vec{p}_{\mu^-} \times \vec{p}_\pi)$, and (4) $\vec{s}_{\mu^+} \cdot \vec{p}_{\mu^+}$.

Correlations (1)-(3) are sensitive to T violation, and are thus perhaps the most interesting. Unfortunately, (1) has a theoretical expectation of less than 10^{-3} both in and beyond the Standard Model, and (2) and (3), while yielding large effects, require measurement of the polarization of the μ^-. Since the effective analyzing power for μ^- is about an order of magnitude lower than that for μ^+, having to measure the μ^- polarization reduces the statistical power for these measurements by a factor of at least 100 from that mentioned above.

Expectations for the longitudinal polarization of the μ^+, (4), are also a few times 10^{-3}, (Wise and Savage, PR **D46**, 5026, 1996). This measurement also suffers from the fact that there is a background due to pion decay in flight that produces longitudinally polarized muons.

As a result of these considerations, we concluded that such measurements would not yield results worthy of the investment necessary to build the calorimeter.

2.2 Radiative decays

There are several radiative decays of charged Kaons which have the potential of allowing T violation studies. Among these are $\pi^+\pi^0\gamma$ and $\mu^+\nu\gamma$. There are also the corresponding modes in which the photon is internally converted, *i.e.*$\pi^+\pi^0e^+e^-$ and $\mu^+\nu e^+e^-$. Observation of correlations such as $\vec{s}_\gamma \cdot (\vec{p}_\gamma \times \vec{p}_\pi)$ for the modes with real photons, or $\vec{p}_{e^+} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\pi^0})$ for those with virtual photons would be indicative of CP violation. For the former, pair production in an external converter and measurement of the angular distribution of the produced e^+ and e^- would yield the photon polarization orientation.

There seems to be a scaling principle at work in these decays that sets the effective branching ratio to be small. While the modes with real photons have relatively large branching ratios - in the 10^{-3} to 10^{-4} range - it is the direct emission (as opposed to internal Bremsstrahlung) which probes short range effects. This reduces the effective rates by about one to two orders of magnitude. Then one must convert the photon into e^+e^- pairs with a thin ($<$ .01 radiation lengths) radiator. Thus the effective branching ratios are in the 10^{-8} area. This is about the same as the rate for the virtual photon modes once one moves to interesting e^+e^- invariant mass levels.

At 10^{-8} branching ratios and beams of Kaons ten times those of E865, one could collect as many as 100 events per hour, or 10,000 events in a ten week run. Such a data sample would permit a statistical uncertainty in an asymmetry measurement on the order of a few percent. Unfortunately theory expects these effects to be an order of magnitude smaller, but this is unexplored territory and may be worth examining as a component of a larger program.

2.3 K to Three π Decays

Differences in kinematic distributions of the pions from $K^+ \rightarrow \pi^+\pi^+\pi^-$ (τ^+), and $K^- \rightarrow \pi^-\pi^-\pi^+$ (τ^-) could occur if CP is not conserved in these decays. Such an observation would indicate direct CP violation, as contrasted to indirect which occurs through K_1^0 and K_2^0 mixing. Since the physics world is heavily investing in experiments to look for direct violation through ϵ'/ϵ measurements in the K^0 decays, a sensitive search in the K^+ sector with an existing beam and apparatus seems justified.

The difference in distributions of which we speak is that of the slopes in the phase space normalized Dalitz plot distributions of the kinetic energy of the odd pion in these decays. (By odd pion we mean the pion whose charge is opposite to that of its parent kaon.) While the majority of theorists feel that the fractional difference in these slopes (Δg) should be smaller than 10^{-5}, there are predictions as large as 10^{-4}, and it is admitted that higher order loops in chiral lagrangian calculations could raise the small predictions as much as an order of magnitude. The present value is $(-7.0 \pm 5.0) \times 10^{-3}$. (Ford, *et al.*, PRL **25**, 1370 (1970)).

E865, with its capability to search for $K^+ \rightarrow \pi^+\mu^+e^-$ at the 10^{-12} level could, after decreasing the beam intensity by a factor of 5 from the present running condition, collect $\sim 10^{10}$ events in each of the two modes in 1000 hours of running. This would allow a measurement of Δg to a statistical uncertainty of $\sim 2 \times 10^{-5}$. This is well within the range of a possible non-zero result within the Standard Model.

The possible limiting factor to such a measurement is systematic effects. Two advantages that an E865-like apparatus has over the detector used in the published measurement is that it allows measurement of the momentum of all final state particles and that it has left-right symmetry. These features allow a reduction in systematic effects in several areas.

At this workshop the effects of the difference in absorption of π^+ and π^- as they encounter material in the apparatus was investigated. It was observed that such a difference would not affect the result at greater than 10^{-4}, but time did not permit this study to be taken further.

It seems that the systematics can be held to better than the 10^{-4} level. More study is necessary before one can know the true limit of these uncertainties.

3 Conclusion

The Charged K Decay in Flight group examined several possibilities for experiments beyond the year 2000. We conclude that while possibilities exist for new experiments at the frontier of particle physics, if they can be performed at all they can be done before the next millennium. While this is perhaps disappointing for the purpose at hand, we do recall that there are 3 years before the turn of the century. If the AGS is to remain viable until then, it is experiments such as we have discussed that will make it be so.

Report of Working Group on Muon to Electron Conversion [1]

W. Molzon

University of California, Irvine

Introduction

We report on a study of the possibility of doing a search for the process $\mu^- A \to e^- A$ with a sensitivity significantly better than current or proposed experiments. This process does not conserve additive quantum numbers associated with muon and electron type leptons and, if seen, would provide the first evidence for lepton flavor violation (LFV). Large improvements have been made in the past 10 years to limits on LFV in both kaon and muon experiments. Further improvement in sensitivity for $\mu^- A \to e^- A$ requires a much higher muon flux than has been previously achieved and a detection apparatus with improved resolution and background suppression. This report discusses the possibility of making such a beam and apparatus at BNL.

Negative muons, when stopped in matter, quickly cascade down to an inner atomic orbital of size comparable to that of the nucleus. The muons will mostly either decay or be captured on the nucleus ($\mu^- A \to \nu A'$); for moderate sized nuclei these processes occur at about the same rate. A third possibility is that a muon, in interacting with a nucleus, converts to an electron. Energy/momentum conservation require that the electron be emitted with energy equal to the muon mass less the Coulomb binding energy. Hence, the experimental signature is an isolated electron of approximately 104 MeV. The momentum transfer to the nucleus is such that it is left in its ground state. Therefore, the process is coherent over all nucleons and the rate is enhanced by approximately a factor of A with respect to muon capture.

If the interaction with the nucleus is mediated by a photon the process is closely related to $\mu \to e\gamma$ decay. In this case, many model calculations predict that the probability of $\mu^- A \to e^- A$ conversion would be about a factor of 100 less than the branching fraction for $\mu \to e\gamma$. Nonetheless, the substantial experimental advantages of $\mu^- A \to e^- A$ experiments may allow an improved sensitivity to the underlying physics using this mode. In any model in which the coupling to the nucleus is through some particle other than a photon, the sensitivity of $\mu \to e\gamma$ to the underlying physics is typically significantly greater than that of $\mu \to e\gamma$.

The decay rate is typically normalized to the kinematically similar process $\mu^- A \to \nu A'$. In both cases, the final state consists of a nucleus and a light lepton with energy equal to nearly the rest energy of the muon. We define the quantity $R_{\mu e} = \Gamma(\mu^- A \to e^- A)/\Gamma(\mu^- A \to \nu A')$. The current best limit derives from the SINDRUM2 experiment at PSI, which set an upper bound on $R_{\mu e}$ at 8×10^{-13} (90% CL). They propose to improve their sensitivity to 4×10^{-14}, with a new beam and new background rejection technique. The best limit on $\mu \to e\gamma$ is expected to come from the MEGA experiment, which will reach a sensitvity approaching 10^{-12}. Hence, a sensitivity below 10^{-16} would improve our knowledge of $R_{\mu e}$ by nearly three

[1] The following people attended all or parts of the working group meetings: V. Abadjev, M. Bachman, D. Bryman, S. Derbenev, R. Djilkibaev, J. Doornbos, R. Fernow, K. Kinoshita, H. Kirk, Y. Kuno, T. Kycia, T. Liu, D. Marlow, W. Marciano, W. Molzon, Z. Parsa, T. Roser, P. Rubin, R. Shrock, J. Szymanski, A. van der Schaaf.

orders of magnitude, and even in models where $\mu \to e\gamma$ is a factor of 100 more sensitive, would yield at least a factor of 100 improvement in sensitivity to the underlying physics.

Briefly, the experiment is done by producing a pulsed beam of approximately 10^{11} low energy negative muons per second and causing them to impinge on a thin target in which a substantial fraction of the beam stops. Detectors are arranged so that only electrons above 53 MeV pass through them and are measured. The energy of 104 MeV electrons which might originate from muon coversion is measured with a precision of a fraction of a percent in a magnetic spectrometer with solenoidal geometry. Background processes which could produce electrons of this energy are discriminated against by detecting the signal electrons only when no beam particles are present in the apparatus, and after all pions in the beam have decayed or have been captured on the nuclei in the stopping target. More detail on the sources of background and a discussion of the ideas for the beam and apparatus are discussed in subsequent sections.

Many of the experimental ideas which motivate the present work are from the proposal of Djilkibaev, Lobashev, and collaborators – the MELC experiment originally proposed for the Moscow Meson Factory.

Theoretical Expectations

Aside from the most fundamental motivation of testing an apparantly exact yet ill-motivated symmetry, a search for $\mu^- A \to e^- A$ tests specific predictions of extenstions to the Standard Model. Many of these extensions are well studied and provide much of the justification for large experimental efforts and proposals for new accelerator facilities. For example, the ideas of supersymmetry are extensively discussed in the context of LHC and NLC experiments. These same models, in large regions of their parameter space, predict LFV with experimentally accessible rates. Some of the early work on predicitions from grand unified supersymmetric models was done by Barbieri and Hall; they predicted rates very close to the present experimental limits. As an example of a recent model calculation which appeared during this workshop, Hisano et al. predict values of $R_{\mu e}$ in the range of 10^{-14} to 10^{-15} and values of the branching fraction for $\mu \to e\gamma$ about a factor of 100 larger than this. Clearly, improving the experimental sensitvity by 2-4 orders of magnitude will have a significant impact on such model calculations, and we may well discover lepton flavor violation.

Background Sources

The process $\mu^- A \to e^- A$ has an extremely clean experimental signature: a monenergetic electron originating from a target in which a muon has stopped. Nonetheless, there are numerous sources of background:

1. Muon decay in a Coulomb bound orbit, with an electron energy endpoint at the same energy as the signal.

2. Radiative pion capture on a nucleus, with a photon energy up to the pion mass, followed by asymmetric conversion in the stopping target.

3. Muon decay in flight.

4. Beam electrons which scatter in the stopping target.

5. Cosmic ray induced electrons

The first source cannot be eliminated and can only be minimized by improving the measurement of the electron energy. The cross section is approximately proportional to $(E_{max} - E_e)^5$. Hence signal/background ratio is extremely sensitive to resolution. A resolution below 1 MeV is necessary; the MELC collaboration has done a Monte Carlo simulation of signal and background with a resolution of 0.8 MeV, and a value of $R_{\mu e}$ of 10^{-16} is only marginally convincing at the level of a few detected events. The consensus of the working group is that the experiment should be very aggressive in energy resolution and try to achieve a resolution approaching 250 keV.

Sources 2-4 derive from prompt processes, with the electron detected close in time to the arrival of a beam particle in the detector. The PSI experimenters eliminated them by vetoing events which contained an in time signal in a scintillation counter in the beam. This clearly will not work with the proposed beam flux of 10^{11} s^{-1}. The conclusion arrived at in the MELC proposal, with which we concur, is that a pulsed beam is necessary, in which the probability of particles arriving at the stopping target during the time that conversion electrons are detected is below about 10^{-8}.

In earlier experiments, the last source, cosmic ray induced electrons, derived largely from photons produced by cosmic rays and converting in the stopping target. It was eliminated by passive shielding and by removing events which had other particle tracks in the detector. Fortunately, the number of background events from this source scales with running time, not with sensitivity. Hence, a cosmic ray suppression factor comparable to that achieved by the SINDRUM2 experiment will result in no background from this source.

In addition to physics backgrounds, there are substantial fluxes of photons, neutrons, and protons from muon capture processes. Protons of low energy (but up to a few hundred MeV/c momentum) are produced in about 1% of muon captures. There are typically 2 photons per muon capture. These sources of detector rates were not significant in earlier experiments, but are a serious problem with 10^{11} muon stops per second.

Experimental Considerations

The two broad areas of improvements necessary to do the experiment we discuss are the high intensity muon beam and a high acceptance detection apparatus capable of rejecting backgrounds. We discuss these two aspects in turn.

Experiments using low energy muon beams have until now been done at low energy machines (PSI, LAMPF, TRIUMF). Typically, the ratio of usable produced muons to targeted protons was of order 10^{-8}. For the MELC experiment, Djilkibaev and Lobashev proposed to put the pion production target in a solenoidal field and collect pions over essentially 4π solid angle. They calculated it should be possible to produce approximately 10^{-4} muons per proton at a low energy proton linac (the Moscow Meson Factory). Unfortunately, that machine, although built, will not be able to operate enough to execute a sensitive experiment. The TRIUMF cyclotron could plausibly accelerate sufficient protons to produce the necessary muon flux; for scheduling and financial reasons we cannot forsee doing the experiment there in the near future. Further, the necessary beam conditions, discussed below, may not be possible. As discussed earlier, PSI has a planned program to reach below 10^{-13}, but fu increases in sensitivity do not seem possible, again because the required beam condi cannot be met.

Recently, it has been realised, perhaps first by the muon collider proponents, tl significantly larger ratio of usable muons to targeted protons can be achieved at BNL. MELC proponents, and subsequently the muon collider proponents, have designed r sources with a production target in a high field solenoid. The flux to be expected is unce: due to lack of measurements of low energy pion production using protons incident on h targets. Model calculations disagree to a factor of 2, but as many as 0.3-1.0 collected m per proton appears possible. With up to 3×10^{13} protons per second available from the / a muon flux well in excess of what is required to reach 10^{-16} sensitivity is possible.

As discussed above, a pulsed beam with intensity between pulses suppressed by 10 required to achieve the necessary background suppression; we call the suppression facto: extinction. The required time structure is short pulses separated by about 1 μsec, wi large macro duty cycle. The AGS offers two possible schemes for producing such a b The RF structure in the machine is 8 buckets in the 2.7 μ sec revolution time. A bun beam extraction has been tested with only one bunch filled. The extinction between bu is below 10^{-5}, and without any care taken to clean up nominally empty buckets, the unf bunches contain $\sim 10^{-3}$ of the filled bunch intensity. Further tests will be done this A second way of making a pulsed beam is to use barrier buckets; this scheme has l successfully used in the microbunching tests for neutral kaon experiments. Tests of ba: buckets with the appropriate time structure could be done during the next fixed ta running period.

A possibility to be considered is that, if the extinction is only 10^{-6} or so, a veto cou active only during the measurement time could be used to further reduce background. T: are several problems with this, including radiation damage, high rates from electrons f muon decay in the stopping target, albedo from the beam dump, etc., which must be stud

An experiment to reach the design sensitivity must deal with the high rates discu: earlier and achieve excellent energy resolution. The SINDRUM2 experiment operate lower rates and sensitivity and used a solenoidal detector surrounding the stopping tar They achieved an electron energy resolution worse than 1 MeV, insufficient for a 10^{-16} ex iment. The MELC proposal also has a solenoidal spectrometer, differing from SINDRU in that the detection apparatus is at a substantial distance along the solenoid axis from stopping target. This reduces the solid angle subtended by the detector for photons. Ic have been proposed to preferentially absorb protons by exploiting the fact that their hel trajectory has the opposite screw sense of that of electrons. The very low energy prot may also be preferentially absorbed by a low Z absorber of modest thickness. Other dete geometries and ways of dealing with the high rates were discussed in the working group : are continuing to be considered. Due to the high rates and need to minimize energy and straggling for electrons, the stopping target is in vacuum. Different detector geomet were discussed with different means of isolating them from the vacuum.

No independent work on the tracking detectors for this experiment has been done the working group. The MELC group has done some tests of tracking chambers and de: studies of ways of isolating them from vacuum. The energy resolution of this appro. is probably insufficient. The tracking detectors in SINDRUM2 achieve a better intri resolution, but may not work at the much higher particle fluxes. Other ideas involving either wire chambers or straw detectors have been discussed and these must be further studied.

Summary

The working group on the muon conversion to electron experiment is enthusiastic about the possibility of doing an experiment at the AGS. The physics motivation is extremely strong. Independent of theoretical considerations, pushing a test of a fundamental symmetry by a factor of 1000 is clearly valuable. In addition, ideas based on grand unified supersymmetric models make plausible the possibility of discovering lepton flavor violation in the range of sensitivity of the proposed experiment.

The BNL AGS is uniquely suited to provide the muon beam required do this experiment. For a variety of reasons discussed above, the experiment cannot be done at the low energy facilites (PSI, TRIUMF, LANL, MMF) where these kinds of experiments have been done. The AGS proton energy allows a significantly higher flux muon beam to be made. Some of the requirements of the muon collider project are consistent with this experiment, and the two groups can benefit from cooperative development of a beam.

There are many issues in the details of the beam and detector which remain to be worked out before a comprehensive proposal can be written. Some of those studies, including beam tests, are being done now. Others of them will be studied during the summer by members of the working group. It is anticipated that a letter of intent could be produced on the time scale of this autumn.

May 1996
Robin Appel

NEUTRINO WORKING GROUP

The most interesting proposal for a current neutrino experiment would be to verify or disprove the LSND signal. However, this is less compelling than it might have been due to the on-going KARMEN upgrade for this purpose (they are adding a second veto layer against cosmic neutrons). They plan to complete data taking in about 2 1/2 years. Given a reasonable time scale for constructing a neutrino experiment at the AGS, KARMEN would be completed before a new experiment could come on-line.

Still, it might be interesting to look at a back-of-the-envelope calculation of the sensitivity of an experiment at the AGS which assumes a detector similar to the E776 detector with an upgraded beam.[1]

- BEAM

  The E776 positive wide band beam had 1.43×10^{19} POT. The upgraded beam would have an integrated intensity of 3×10^{20} POT if run for 2400 hours. This gives a factor of 21 increased beam.

- NUMBER OF EVENTS

  One can simply scale the number of events and the predicted background by the factor of 21 due to increased beam. E776 had 6676 ν_μ events, 136 ν_e events, and a predicted background of 131 ± 11(stat) $\pm$ 20(bg stat) $\pm$ 19(syst) ν_e events. The proposed experiment would see 140200 ν_μ events, 2856 ± 53 ν_e events with a background of 2750 $\pm 50 \pm 420 \pm 400$ ν_e events. This would give an upper limit of 580 oscillation events, by adding the two uncertainties in the number of ν_e events.

- PROBABILITY OF OSCILLATION

  The probability of oscillation is the ratio given by the upper limit of the number of ν_e events divided by the number of ν_μ events - with a correction of $.95 \times$ the number of ν_e events, since acceptance for ν_e is $\sim 5\%$ higher than that for ν_μ. This calculation gives an oscillation probability of .0041 from ν_μ to ν_e.

[1] Suggested by Tom Roser.

- SENSITIVITY

  The average ν_e energy in this beam is 1.4 GeV. A calculation of Δm^2 for L(km)/E(GeV) = 1/1.4 for $\Delta m^2 < 2$ shows that it is not possible to cover the LAMPF signal region with this upgraded AGS beam. (See Figure 1) However, improvement can be made by moving the detector to 1.5°, as suggested by the E889 collaboration. This lowers the average neutrino energy to approximately 1 GeV, although it reduces beam flux on the order of 50%. Calculating the sensitivity with these changes gives a probability of .0047 of oscillation. A further improvement can be made by moving the detector to 1.5 km from the target. Again we get a reduction of neutrino flux (by a factor of 1.5^2), but there is a compensating increase in L/E which brings the sensitivity closer to the LAMPF signal region.

One cannot prove that this experiment might be successful by these naive calculations of sensitivity which do not reference the energy spectrum and acceptance, but this does suggest the possibility that such an experiment could succeed given further optimization of the detector, especially if the background could be reduced.

Search for Strangeonium Hybrids

-- Exotic Mesons --

" Instant " Report of the Working Group for Strangeonium Hybrids

S. U. Chung, R. W. Hackenburg, Y. Y. Lee, K. Olchanski,
P. H. Pile, D. P. Weygand, H. J. Willutzki
BNL

G. Gutierrez
FNAL

V. L. Korotkikh, M. A. Kostin, A. I. Ostrovidov
Institute for Nuclear Physics, Moscow State University

T. Barnes
ORNL

G. S. Adams, M. Nozar, D. White
Department of Physics, Rensselaer Polytechnic Institute

J. Doornbos
TRIUMF

J. P. Cummings, J. P. Dowd, P. Eugenio
Department of Physics, University of Massachusetts Dartmouth

K. K. Seth
Department of Physics, Northwestern University

N. M. Cason
Department of Physics, University of Notre Dame

K. Blackett
University of Tennessee, Knoxville

1. Motivation

Despite universal agreement that Quantum Chromodynamics is the theory describing hadron physics, very little is known about its properties in the low momentum transfer region as epitomized by hadron spectroscopy. Our understanding of hadron spectroscopy is based on the constituent quark model in which baryons are made out of three quarks and mesons out of a quark-antiquark pair. In addition to these conventional hadrons QCD suggests the existence of new types of hadronic matter with gluonic degrees of freedom. These are glueballs - mesons with no quark content, hybrids - mesons with a pair of valence quarks and a gluon, and four-quark states. One of the most fundamental qualitative questions about QCD is whether these states do in fact exist.

The most promising approach to find hybrids is to look for mesons with quantum numbers not allowed by the constituent quark model (exotics). In the quark model, the spins of the constituents combine to give a total spin S = 0 or 1. In addition the quark and antiquark will have a relative orbital momentum L. This leads to a meson spectrum with quantum numbers $J^{PC} = 0^{-+}, 1^{--}, 1^{+-}, 0^{++}, 1^{++}, 2^{++}, 2^{-+}, 1^{--}, 2^{--}, 3^{--}$ etc. In contrast, the lowest lying hybrid meson states will have $J^{PC} = 0^{++}, 0^{-+}, \underline{0}^{+-}, \underline{0}^{--}, 1^{++}, \underline{1}^{-+}, 1^{+-}, 1^{--}, 2^{++}, 2^{-+}, \underline{2}^{+-}, 2^{--}$. The underlined states are manifestly exotic and therefore prime targets for experimental searches.

Theory predicts masses for hybrid mesons containing u and d quarks around 1.9 GeV and 2.1 GeV for those containing s quarks with an estimated uncertainty between 50 MeV and 100 MeV. In the case of glueballs two lattice gauge calculations have been completed. The UKQCD collaboration predicts masses for the $J^{PC} = 0^{++}$ and 2^{++} glueballs of 1.55 GeV and 2.27 GeV while the IBM group puts them at 1.74 GeV and 2.36 GeV.

Experimentally, there exist at present three isovector $J^{PC} = 1^{-+}$ hybrid candidates, the $\pi_1(1300)$, $\pi_1(1620)$ and $\pi_1(2000)$ *) , all in need of

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*) *Our proposed notation of* J^{PC} *- exotics differs from the Particle Data Group convention. The name of the particle is determined by the combination of P and C. Hence, an isovector* $J^{PC} = 1^{-+}$ *state is denoted* π_1*, while its isoscalar partners are given the names* η_1 *and* η'_1*. Likewise, an isovector* $J^{PC} = 0^{+-}$ *state, to take another example, is denoted* b_0*, while its isoscalar partners are given the names* h_0 *and* h'_0*.*

confirmation. The KEK group observes a state at a mass of 1323 MeV and 143 MeV width in the $\pi^-\eta$ channel, produced via natural-parity exchange. This result is in conflict with an earlier GAMS result at CERN in the $\pi^0\eta$ channel, which showed a 1^{-+} state with unnatural-parity exchange. The VES experiment at IHEP also studied the $\pi\eta$ channel but they report no significant 1^{-+} state in the 1.3 - 1.4 GeV region. Instead, they see a 1^{-+} state at 1.620 GeV decaying into $\pi\rho$ and $\pi\eta'$, produced via natural-parity exchange. The BNL-E852 collaboration finds that the $1^{-+}\pi\rho$ wave is very much reduced compared to the $a_2(1320)$ signal, in contrast to the VES results. The BNL-E818 experiment reports a 1^{-+} state around 1.9 - 2.0 GeV coupling to the $f_1(1285)\pi$ channel, with a rather rapid increase of the phase relative to the 1^{++} wave. The VES experiment also finds a broad 1^{-+} $f_1(1285)\pi$ state in the 1.6 - 1.8 GeV mass region but they do not report a study of its phase motion.

The state at 1323 MeV seen by the KEK group is at the moment under intense scrutiny by the BNL E852 group. The partial-wave analyses in both the $\eta\pi^-$ and $\eta'\pi^-$ final states indicate presence of an exotic 1^{-+} wave. It is hoped that the situation will soon be very much clarified by the impending results from partial-wave analyses on the BNL-E852 data, especially on the data sample based on the 10^9 triggers which the collaboration took recently; the decay channels under study include $\pi\eta$, $\eta'\pi$, $\eta\eta$, $(\pi\pi\pi)^-$, $b_1(1235)\pi$ and $\omega\eta$.

In addition, new results are expected from the analyses being carried out on the IHEP data taken by the VES and GAMS groups. Further new information should be forthcoming from the massive statistics being accumulated by the CRYSTAL BARREL and OBELIX experiments at LEAR in proton-antiproton annihilations at rest and in flight. The WA76 collaboration using the OMEGA spectrometer at CERN, and its extension WA91, have been collecting data since 1991 to search for exotic mesons in central production - so far they report no 1^{-+} states in their data. All these efforts are expected to yield a more complete picture of the role of valence gluons as constituents of hadrons. However, all these experiments concentrate on final states produced by an initial system containing only light, non-strange quarks. A scan of the Review of Particle Properties reveals that very little is known about gluonic strangeonia.

2. Hybrid Strangeonia

Recently the original flux-tube model of Godfrey and Isgur has been extended to the strangeonium sector by Close and Page with gluonic excitations having both exotic and non-exotic quantum numbers. As shown in the following tables, their predicted masses range from 2.15 to 2.25 GeV and widths from 120 to 575 MeV. In particular, they predict a narrow (width 120 MeV) non-exotic gluonic strangeonium at mass 2.15 GeV with quantum numbers $J^{PC} = 2^{-+}$. It would be exciting indeed to find such an object.

I^G	J^{PC}	State	Decay mode	Decay L	Width (MeV)
0^-	0^{+-}	$h'_0(2150)$	$K_1(1270)$ Kbar	P	400
			$K_1(1400)$ Kbar	P	175
0^+	1^{-+}	$\eta'_1(2150)$	$K_1(1270)$ Kbar	S,D	40, 60
			$K_1(1400)$ Kbar	S	250
0^-	2^{+-}	$h'_2(2150)$	$K_2(1430)$ Kbar	P	90
			$K^*_1(1270)$ Kbar	P	30
			$K_1(1400)$ Kbar	P	70

Table I. Exotic Strangeonium Hybrids

I^G	J^{PC}	State	Decay mode	Decay L	Width (MeV)
0^+	0^{-+}	$\eta'(2150)$	$K^*_2(1430)$Kbar	D	20
			$K^*_0(1430)$Kbar	S	400
0^-	1^{+-}	$h'_1(2150)$	$K^*_2(1430)$Kbar	P	70
			$K_1(1270)$ Kbar	P	250
			$K^*_0(1430)$Kbar	P	125
0^+	2^{-+}	$\eta'_2(2150)$	$K^*_2(1430)$Kbar	S	100
			$K_1(1270)$ Kbar	D	20

Table II. Non - exotic Strangeonium Hybrids Total intrinsic spin = 1

Monte Carlo simulations of the typical reaction $K^- p \rightarrow \eta'_2(2150)\Lambda$,where the $\eta'_2(2150)$ decays into $K^*_2(1430)$ Kbar and the $K^*_2(1430)$ decays into the $K\pi$ final state, have shown that acceptances of 10 % (this is again very conservative) can be expected. Thus with a run of 5000 hours and a two-foot liquid hydrogen target a sensitivity of approximately 330 events / nbarn is achievable. This represents an improvement of almost two orders of magnitude over the best data set to date on $K^- p$ interactions obtained by LASS at SLAC.

I^G	J^{PC}	State	Decay mode	Decay L	Width (MeV)
0^+	1^{++}	$f'_1(2150)$	$K^*_2(1430)$Kbar	P	125
			$K_1(1270)$ Kbar	P	70
			$K_1(1400)$ Kbar	P	100
0^-	1^{--}	$\phi(2150)$	$K^*_2(1430)$Kbar	D	20
			$K_1(1270)$ Kbar	S	60
			$K_1(1400)$ Kbar	S	125

Table III Non - exotic Strangeonium Hybrids Total intrinsic spin = 0

It should be borne in mind, however, that even hybrids containing only u and d quarks are expected to have substantial decay modes into strange particle final states, e.g. one third of the decays of the $J^{PC} = 1^{-+}$ $\pi_1(2000)$ and $\eta_1(2000)$ and all the decays of the $J^{PC} = 1^{--}$ $\omega(2000)$ are predicted into strange particles. The only way to distinguish between strangeonium hybrids and non-strangeonium hybrids is to start with an initial state that contains already a strange quark such as the K^-.

3. Sensitivity of the proposed Experiment

A systematic search for these gluonic strangeonia will require a superconducting RF-separated K^- beam. Such a beam was successfully operated at CERN and the superconducting cavities could be used to build the beam at BNL in the A1 line leading to the Multiparticle Spectrometer (MPS). The cavities are mothballed in the ISR tunnel and could be made available to us. Initial studies have shown that a two-cavity beam would fit into the A1 line provided one chooses the phase difference between pions and kaons as 120 degrees instead of the usual 180 degrees in the second cavity.

We have estimated the expected kaon flux for the A1 beam line at a beam momentum of 12 GeV/c as 2.5×10^5 / burst, assuming 2.5×10^{13} protons on target. This should be considered as a very conservative estimate. If the AGS can be operated in a microbunch mode, this flux could be increased substantially by using the two cavities as one, such reducing the unavoidable beam losses associated with the usual two cavity configuration.

AGS-2000: Summary of Discussion

Baryon Spectroscopy / Rare Eta Decays

May 18, 1996

The working group for Baryon Spectroscopy and Rare Eta Decays was composed primarily of members of the Crystal Ball Collaboration (CBC), which held a collaboration meeting during the week. About 20 persons were present throughout, with up to an additional ten persons who attended periodically and participated in the discussions. The group heard presentations from several theorists, including Barry Holstein, Steve Cotanch, Ted Barnes, and Franco Iachello, and a joint session was held with the p-bar Working Group.

The CBC is preparing for an extensive program of studies of baryon spectroscopy with the Crystal Ball detector, beginning in 1997. The $\pi^- p$ and $K^- p$ reactions will be used to form non-strange and strange baryon resonances up to masses greater than 2 GeV, and their decays into neutral channels will be mapped out with the CB detector. For the $\pi^- p$ reaction, the decay channels include $n\gamma$, $n\pi^0 \rightarrow n2\gamma$, $n\pi^0\pi^0 \rightarrow n4\gamma$, $n\omega \rightarrow n\pi^0\gamma \rightarrow n3\gamma$, etc. Similar processes leading to a neutron and multiple photons will be detected for the $K^- p$ reaction.

The initial set of data will be obtained on the C line. The C line is barely adequate for only the lowest few N^* and Δ resonances formed in $\pi^- p$ reactions ($M < 1540$ MeV), but can reach a little higher in mass ($M < 1650$ MeV) for Λ and Σ resonances formed in $K^- p$ reactions. In order to complete the full program outlined in the proposals for E913/E914, however, it is necessary to install the Crystal Ball on the D line as soon as possible after the initial set of measurements. Observation was made that Ξ^0 baryons up to $M = 1650$ MeV could also be studied through the (K^-, K^0) reaction at the highest momenta on the D line. The Working Group was informed and became very excited about an option to use the CB detector with a $\bar{p}$ beam in order to investigate the existence of a possible glueball meson at 2230 MeV, as suggested by the p-bar Group. This experiment will also require the D line. In light of all three circumstances, the Baryon Spectroscopy Working Group strongly urges the following two items:

> **The Crystal Ball detector be installed on the D line as soon as possible after 1998, and remain active for at least two years, in order to complete the program in baryon spectroscopy, including extensions to Ξ baryons.**
>
> **The Crystal Ball detector be used jointly on the D line after 1998 with a $\bar{p}$ physics collaboration in order to search for and/or confirm a possible meson resonance at 2230 MeV, which may be a glueball.**

Several hardware upgrades were discussed for use with the baryon spectroscopy program prior to the year 2000. These included an endcap that would nearly complete the solid-angle coverage of the CB, thus enabling a more complete identification of events and suppression of backgrounds from strong channels into weaker ones. A magnetic field and tracking chambers could also be added beyond the detector. These would permit some detection of charged particles, particularly those associated with decays into vector mesons, or sequential decays of high-lying N^* and Δ resonances through lower ones. More benefits would come by placing tracking chambers and a magnetic field internal to the Ball.

The Working Group then addressed several possible extensions of the baryon spectroscopy program that open up opportunities for exciting new physics. The two principal areas involve measurements of polarization observables for the reactions already in the program, and a set of particular rare decays of the eta meson. Each area will entail the implementation of new hardware features.

Polarization Observables

The baryon mass spectrum is very complex, with many resonances of different spin and parity and large widths that overlap substantially. It is a credit to the theorists who subject the data to phase-shift analyses that we know as much as we do. Nevertheless, much remains unsatisfactory, and the topic has become an area of sharply enhanced experimental activity. The Crystal Ball will extend the data base with unprecedented precision. However, the initial program will be incomplete in essential ways.

The baryon spectrum has also become a fertile area of theoretical activity. As outlined by Iachello, current models fall generally into four classes: (A) three quarks in a bag with a harmonic oscillator potential and perturbations; (B) flux-tube models with rotations and vibrations as the primary modes of excitation; (C) three quarks in a bag with a hyper-coulomb potential and perturbations; and (D) diquark-quark configurations. Roughly, before perturbations, one feature is common to all models: groups of states are equally spaced in mass and form a sequence of increasing orbital angular momentum, i.e., 0^+, 1^-, 2^+, etc. However, model B has a feature that is not present in the basic structure of the others, namely a set of spatial 1^+ states degenerate with the 1^- group, and a set of spatial 2^- states degenerate with the 2^+ group. Evidence for such "parity doubling" is currently very ambiguous. In order to understand fully the pertinent degrees of freedom and the underlying symmetries that are realized in nature, we must identify *all* of the baryon states and elucidate their properties.

Most data to date are limited to cross sections, which provide very limited sensitivity to spin degrees of freedom. This situation is not satisfactory, but can be overcome. The Working Group thus discussed several methods for looking at polarization observables. For kaon beams, the self-analyzing feature of the Λ and Σ hyperons could be utilized, but details for implementing such a scheme were not laid out. Focus was instead given to the important pion-induced reactions. In this case, a polarized hydrogen target will be required. The only relevant observable is the analyzing power A_y, which would require a transversely polarized target. The Crystal Ball is exceptionally well-matched to such experiments, because the complete azimuthal coverage provides both of the required "spin-up" and "spin-down" yields simultaneously. The polarization data will be enormously helpful in determining the spins of the resonances, and they will also provide unique insights into the internal structure of the resonances and critical tests of the models used to describe them.

Members of the Crystal Ball Collaboration have had very extensive experience in polarization measurements and polarized targets. Consultations with target experts lead to the conclusion that, while challenging, the design of a target suitable for the Crystal Ball is feasible. A very rough estimate of the cost is about $800K, depending considerably on how much hardware could be obtained from collaborators and other laboratories. The cost is considered to be very modest for the physics, and so the Working Group recommends:

> **Proposals should be developed and funds obtained for the design and implementation of a polarized target to be used in the Crystal Ball detector for the measurement of polarization observables.**

Quark Mass Project

The quark masses are basic parameters in QCD and the Standard Model. They cannot be measured, and theories for calculating them do not exist. Currently, the values are obtained from a blend of theory and experiment, in particular measurements of quantities that arise from the breaking of SU(3) and SU(2) symmetries. The Crystal Ball project will obtain baryon masses with far greater precision than in the past, and such new values will be critical to future evaluations of the quark masses.

The major theoretical tool, chiral perturbation theory, depends strongly on several quantities that must be determined from experiment. Two experiments of interest to us are particularly important. These involve the decays $\eta \to \pi^0\gamma\gamma$ and $\eta \to 3\pi^0$. The CB is an exceptionally fine detector for these rare decays, and the feasibility of obtaining the required sensitivity will be assessed during the baryon spectroscopy program.

Rare Eta Decays

The weak and rare decays of pseudoscalar mesons can provide very sensitive tests of basic symmetries. The tests may be broadly grouped into four classes, depending on the symmetry that can be violated. The rare eta-meson decay $\eta \to \pi^0\mu^+\mu^-$ provides us with a unique test of CP invariance of class 4: C and T violation with P invariance. It compares favorably with another test of class-4 CP invariance, namely the transverse muon polarization in $K^+ \to \pi^0\mu^+\nu$. The latter is a flavor-changing decay, while the eta decay conserves flavor. The interest in this eta decay is particularly strong in that its rate either provides a good upper limit to C invariance or allows a measure of lepton charge asymmetry outside the Standard Model, thus making the experiment a win-win situation. Interest is also stimulated by the baryogenesis problem of cosmology. The experiment is thus uniquely suited as an AGS-2000 project.

The accuracy that is desired corresponds to a branching ratio of 10^{-10}. We are considering a detector that has been upgraded with an internal magnetic field and a tracker to measure the momentum of the charged leptons. The AGS can provide the necessary flux of π^- mesons at $p_\pi = 700$ MeV/c to produce a copious supply of eta mesons via the reaction $\pi^-p \to \eta n$. No other detector can match our detection scheme and event rate. The field and tracker would be beneficial to the baryon spectroscopy program as well. Cost estimates are not clear at this point, due to some cost-saving ideas that originated during the Workshop.

Another interesting test of CP invariance is the forbidden decay $\eta \to 4\pi^0$. It is also not allowed by parity conservation down to the level of 10^{-7} where P-violating weak interactions can occur in η decay. However, the small phase space for the decay pushes the significant decay rate down to about 10^{-11}!

The signature for the decay consists of 8 photons, each about 75 MeV, with four pairs of π^0 invariant mass which reconstruct to an η. There are no known backgrounds. The Crystal Ball detector has excellent energy and angular resolution to enable a proof-of-principle test for this decay to the level of about 10^{-9}. If favorable, a new detector with finer segmentation might be required for the final measurements.

Summary of the Antiproton Working Group

Group Members and Contributors:
Ted Barnes, Billy Bonner, Oleg Dalkarov, Slava Derbenev,
Jaap Doornbos, David Goodwin, Gaston Gutierrez, David Hertzog[†],
Y.Y. Lee, Gerald Miller, David Peaslee, Phil Pile, Klaus Röhrich,
Sergei Sedykh, Kam Seth, Gerald Smith, David Urner, Bob Welsh

[†] Contact Person, hertzog@uiuc.edu.

July 23, 1996

1 Executive Summary

The antiproton working group was organized several months in advance of the formal workshop. In addition to two intermediate meetings which took place at Brookhaven, extensive advance preparation was communicated electronically. Representation in the group included experts with vast experience using antiprotons at LEAR and at FNAL covering topics ranging from trapped ultra-cold antiprotons to resonant charm production. The group carefully surveyed a considerable number of options. We set stringent criteria based on answers to the following questions:

- Is the physics compelling not only to us, but also to a broader community?
- Will we achieve a crisp result that has a clear impact?
- Is our method the best way to attack the physics?
- Is the Brookhaven AGS complex uniquely able to serve the needs of this experiment?
- What is the competition?

In the end, we found four "driving" physics problems to be explored further and several others that would be easily accomodated given the capital investment in the main programs.

On an equal footing with the investigations of potential physics experiments, is the issue of whether Brookhaven, as an antiproton source, is competitive with other facilities in the world. Given that the CERN-LEAR complex has existed for more than a decade, and that the FNAL antiproton accumulator has permitted a limited non-collider physics program to exist, we carefully addressed the important issue of what role Brookhaven might play. Not surprising to many of us, the ever-increasing performance of the Brookhaven AGS has resulted in the potential for the world's most intense source of low-energy antiprotons. The working group examined several schemes for delivery of such antiprotons and unanimously agreed that the most attractive option to be pursued involves utilizing the recently commissioned Booster as a collector and cooler machine. It is technically feasible at very modest cost and would result in delivery of pure, cooled, and very intense antiproton beams in the range from 0.05 - 5.2 GeV/c. This covers our entire physics region of interest. Compared to other world-wide facilities, the Brookhaven Antiproton Complex (BAC) which we recommend below would represent the next-generation source. It would feature higher intensities and longer available running times. Uniquely, it would be built to match a specific physics program, as opposed to being a derivitive of a collider's physics program.

In summary, we envision a phased antiproton program at Brookhaven, beginning with use of existing facilities and building in stages toward the full BAC concept. The rest of the document outlines individually the phases, sequenced by both time and our estimation of a natural evolution.

2 Phase 1: Physics using the existing D6 line

The discovery of the glueball is widely recognized as an important confirmation of the natural consequences of the non-abelian nature of QCD. In the past few years, experimental and theoretical information have begun to identify the scalar glueball. Its mass is in the range 1.5 - 1.7 GeV and two candidate states fulfill many of the expectations. In 1995, the IBM lattice QCD group has not only achieved a remarkably precise determination of the light glueball masses, but they have also succeeded to extract a glueball decay width, based on the assumption of $gg \rightarrow (PS)(PS)$, i.e, two pseudo-scalar mesons. The result of $\Gamma \approx 100$ MeV is highly encouraging for active searches; it means that the glueball production rate will be large enough to be "produced," yet small enough to "measure." Additional consequences of the calculation(s) are that the tensor glueball is predicted to lie in the 2.2 - 2.5 GeV range. Our expectation is that the width will also be fairly narrow.

On the experimental side, the BES collaboration in Bejing has confirmed[1] the unusually narrow state called the $\xi(2230)$ which was originally observed by MARK III. The BES group, in addition to seeing the ξ in $K\overline{K}$, has observed it in the non-strange final states, $\pi\pi$ and $\overline{p}p$. They report a width of approximately 20 ± 20 MeV with an error consistent with zero. The BES Collaboration argues for a tensor glueball interpretation of the ξ; the decays appear flavor symmetric, the width is narrow, and the production channel is considered ideal.

In the past, several searches for the ξ have taken place in formation experiments of the type $\overline{p}p \rightarrow \overline{K}K$ in both the charged and neutral channels. Modest limits on the ξ observation have been set, but only following assumptions of width hypotheses. Given the experimental evidence on the width, such inputs to the fits are at best intelligent guesses.

The Jetset experiment at LEAR has recently scanned the ξ region using the final state channels $\phi\phi$, K_sK_s and $\eta\eta$. None of the ξ-search data is published, although preliminary hints in some of the ongoing analyses do indicate signs of structure in some of the channels. The statistics, however, are miserably wanting. In Jetset's finest scan of the region, little over 150 hours was spent on a 10-point momentum scan around the ξ mass in 5 MeV/c steps. Additionally, the detector suffered from an incomplete acceptance of only about 2-4%.

In one of the most straight forward two-meson final states, $\eta\eta \rightarrow 4\gamma$, this limitation could rather trivially be overcome by use of the Crystal Ball detector which was recently acquired by Brookhaven. If placed in the D6 line where 10^6 antiprotons per spill can be expected at 99% purity a definitive ξ search could be mounted in 1000 hours of running with little capital investment. If the ξ is found, and if it is indeed narrow, it will be a truly

[1] Phys. Rev. Lett. **76** (1996) 3502

important hadronic object. Further study of the state in other final-state channels would aid in pinning down its physical origin.

3 Phase 2: Physics from Booster-cooled antiprotons

For this and the following sections, we focus on a unique opportunity to utilize the newly constructed Booster ring during its idle time between AGS cycles. The Booster as realized has an excellent magnetic lattice, twelve straight sections (one presently unused), and an ultra-high vacuum system. Using the new target area constructed for the muon $(g-2)$ experiment, together with a lithium lens, we estimate that 5×10^7 antiprotons can be produced, collected, and directed back toward the Booster for each $2.5 \times 10^{13} ppp$. What is required is a lithium lens system (possibly obtainable from Novosibirsk), a transfer beam line back to the Booster (the $g-2$ line is typical of the need), modest plumbing modifications, and a stochastic cooling system (a design using only *one* straight section has been proposed). Under this scenario a high-intensity source of cooled antiprotons will exist in the Booster. Cooling can be done in 100 msec. The rest of the time can be used for slow "delivery" to the experiment prior to the next AGS cycle at which time the Booster would be "emptied." The precise momentum at which we would collect the antiprotons (or alternatively deccelerate them) is motivated by our physics program which is described next. A schematic layout of the BAC is shown in Figure 1.

3.1 J/ψ-Nuclear Cross Sections

RHIC is dedicated to establishing the existence of Quark Gluon Plasma (QGP), a novel state of hadronic matter. In order to achieve this objective we must identify the tell-tale signals of QGP formation. A favorite among the proposed signals is the "suppression of J/ψ production", first suggested by Matsui and Satz, and later observed by NA38 at CERN. The suppression is supposed to arise from the transformation of the confinement part of the $\bar{q}q$ potential from being proportional to r to a weak Debye-screened potential proportional to $exp(-r/r_D)$, with $r_D \propto 1/\text{temperature}$.

In order to make sure that the J/ψ suppression observed at CERN (precursor to QGP?) and the suppression expected at RHIC is indeed due to QGP formation, and not due to the Glauber-type attenuation of J/ψ in its passage through normal nuclear matter, it is necessary to measure the J/ψ cross section at modest momenta at which it is likely to be formed in heavy ion collisions. The only existing measurements bearing on $\sigma(J/\psi - N)$ are the photoproduction and hadroproduction experiments done at Fermilab energies (100-800 GeV). As Brodsky and Müller have pointed out, "the effective cross section, σ extracted using [Glauber analysis of] these data has little to do with J/ψ scattering on a nucleon", "because what passes through the nucleus is not J/ψ". The $\bar{c}c$ pair formed in the pointlike production has no time to hadronize into a normal size J/ψ before the high momentum of the pair takes it out of the nucleus (color transparency). The cross sections derived from these measurements (1-5 mb) are surely lower limits of the actual cross sections.

It is extremely important to determine the true $J/\psi - N$ cross sections because if they are $\geq 10\ mb$, Glauber attenuation in nuclear matter would suffice to explain the observed suppression in heavy ion collisions. If, on the other hand, $\sigma(J/\psi - N) \leq 5\ mb$, some unconventional phenomenon, such as QGP formation, will indeed have to be invoked.

We claim that the best way to avoid the feed-down and color transparency problems inherent in the high energy inclusive J/ψ production experiments is to form the low momentum J/ψ exclusively in the nucleus via $\overline{p}$ annihilation on nuclear protons. The $\overline{p}p \rightarrow J/\psi$ reaction forms 3.1 GeV mass J/ψ with 4.1 ± 0.3 GeV/c momenta. The $\overline{c}c$ pair hadronizes to J/ψ within 0.5 fm of its formation and the J/ψ truly interacts with the nucleons on its way out.

We propose that the stochastically cooled antiprotons in the Booster, accelerated to the proper momenta (3.6 - 4.5 GeV/c), be used to measure cross sections for the reaction

$$\overline{p}A \rightarrow (A-1) + l^+l^-,$$

with the detected leptons being electrons and/or muons. We estimate that with ~ 1 radiation length solid nuclear targets we can scan the Fermi-broadened J/ψ over its $\pm$250MeV width in ~ 500 hours to obtain a 5% measurement of $\sigma(J/\psi - N)$ for a single nuclear target. Of course this time estimate relies on assumptions of detector acceptance. In order to test the validity of our assumption of negligible color transparency effect and our method of Glauber analysis of the data to extract cross sections, several nuclear targets, from C to Pb, need to be studied.

It is important to note that because of the physics considerations mentioned above, these measurements cannot be made anywhere else in the world.

3.2 Other interesting physics opportunities

The working group spent a fraction of its time and effort discussing other opportunities which would naturally arise with the availability of a clean and intense *extracted* antiproton beam in the previously unavailable momenta regime from 2.0 to 5.2 GeV/c. For example, it proves to be a relatively straight forward task to make a detailed measurement of the reaction $\overline{p}p \rightarrow \overline{Y}Y^*$ with the specific focus on the production of the $\Lambda(1405)$ state, long an enigma of physics. Under model assumptions that the $\Lambda(1405)$ is alternatively either a 3-quark excited lambda or that it is a bound $K-N$ system, calculations of the cross section and observables greatly differ. If we have a more complete detector, including a hermetic electromagnetic calorimeter, then the radiative decay can be studied. Our simulations indicate that we can obtain approximatey 400 radiative events per day, an order of magnitude greater than the proposed CEBAF experiment which is aimed at solving the long-standing mystery of the $\Lambda(1405)$.

In a related hyperon-antihyperon test, we remark briefly on the possibility of studying a very unusual reaction, namely $\overline{p}p \rightarrow \overline{\Omega^-}\Omega^-$. We estimated the cross section, considered the most favorable decay modes and obtained count rates. In principle one could produce up to 100 events per hour using the extracted Booster beam. With reconstruction and acceptance efficiencies considered the number would probably be ten times lower. Since the Ω^- hyperon is truly a pure strange-quark system (unlike the ϕ meson which has some non-strange quark mixing), the reaction would only proceed through complete annihilation of the incoming quarks. This would presumably occur on a very short distance scale and thus would be a very high density system of quarks and antiquarks.

4 Phase 2: Physics with cold antiprotons

In the past several years, great advances in techniques to trap and cool antiprotons have taken place. Achievements such as the trapping of up to 10^6 $\overline{p}$ have been made. In parallel, advances in the trapping of large numbers of positrons are taking place. The purpose in these activities is eventually to form large numbers of antihydrogen atoms, $\overline{H}^0$. With such a system to study, very interesting CPT tests can be made in studies of the gross structure, fine structure, Lamb shifts and hyperfine structures in H^0 and $\overline{H}^0$.

Recently, the discovery of antihydrogen was made using in-flight antiprotons at LEAR[2]. Such anti-atoms are not suitable for high-precision CPT studies, but the overwhelming and positive public response certainly indicates the widespread interest in continued studies of this unique atomic system. Two efforts at CERN aim to make cold antihydrogen. They presently rely on LEAR (which closes at the end of 1996) from which approximately 10^9 antiprotons can be obtained in about 30 minutes. These opportunities are available for limited times per year. If the proposed CERN AD project is realized (antiproton decelerator) which would replace LEAR the situation will "at best" remain the same from the point of view of intensity. One would anticipate that longer running periods may become available.

At Brookhaven, following the Booster transfer scheme outlined above, one could produce cooled antiprotons with energies as low as 1 MeV at intensities of up to 10^7 per AGS cycle. The antiproton trapping groups are able to stack such antiprotons in time periods that can be made commensurate with such cycles, or in several cycles. As a point of comparison, consider the potential accumulation of 10^7 antiprotons every 10 seconds. This represents a 20-fold advantage over CERN. Here we have included loss in the deceleration process of a factor of 5 and we have further assumed that only 1 in 3 AGS cycles is accepted into the traps. Consequently, there is considerable room for further advantage up to the antiproton production limit.

In order to achieve 1 MeV cooled antiprotons, we anticipate that both stochastic and electron cooling methods would be required. Slava Derbenev in our working group proposed a detailed layout for the Booster that would house both systems. Followup work will take place.

The physics of cold antihydrogen is documented in several reports [3] and is the subject of proposals, for example one recently prepared for CERN by G. Gabrielse and collaborators. A wealth of opportunites arise in this interdisiplinary field which gathers experts in atomic and particle physics on an assault on a very novel state of matter.

In the plans, two distinct groups are approaching the production and testing of antihydrogen in different manners. The Gabrielse group intends to fill nested cyclindrical Penning traps with antiprotons and positrons. Then they will merge the samples watching for the rapid process $\overline{p} + e^+ + e^+ \rightarrow \overline{H}^0 + e^+$, as well as laser assisted radiative recombination $\overline{p} + e^+ + h\nu \rightarrow \overline{H}^0 + 2h\nu$ and the slower process $\overline{p} + e^+ \rightarrow \overline{H}^0 + h\nu$.

A second group, led by Mike Holzscheiter, would embark on a more elaborate approach involving positronium formation and slow collisions of positronium atoms with antiprotons. This is more energetically favorable as a formation method, but requres the extra effort to establish a strong positronium source.

In either case, if formed, neutral antihydrogen (or hydrogen for that matter) must be trapped. This is successfully demonstrated with ordinary hydrogen by use of a magnetic field gradient trap (a Ioffe trap). In such a system the Rydberg has recently been measured to extrodinary accuracy. It is conceivable to compare the Rydberg constant to the "anti-Rydberg" at a level of 10^{-12} or better in the future.

These ideas in this new and rich field are essentially untapped. In our brief outline given here, we have failed to provide the richness of thought that has gone into the program thus

[2]Phys. Lett. **B368** (1996) 251

[3]e.g., "Antihydrogen Physics", Phys. Rep. 241 (1994) 67.

far. To advance the project further at Brookhaven, we will require considerable technical work mainly from the machine physicists. If the cold antiprotons can be delivered, there is already a well-described and compelling physics program waiting for the "beam."

5 Phase 3: A test of direct CP violation in the decays of hyperons and antihyperon

The decay properties of hyperons and antihyperons should be the same in the limit of CP symmetry. These decays are weak and parity violating, manifest by an anisotropic angular distribution of the decay baryon with respect to the hyperon spin axis. If CP is violated, one would expect that the anisotropy of the hyperon decay would be different from that of the antihyperon.

John Donoghue and collaborators have promoted hyperon-antihyperon decay analysis tests as excellent opportunities to look for *direct* CP violation. In a "model-independent" analysis, their studies lead to a set of experimental "tests" that can be made and to corresponding sets of (model-dependent) predictions of these effects. The relevant CP test that we propose to exploit is one which compares the decay angular distributions of lambdas and antilambdas following a reaction of the type $\overline{p}p \to \overline{\Lambda}\Lambda$. Using the definition

$$A = \frac{\alpha + \overline{\alpha}}{\alpha - \overline{\alpha}}$$

theoretical predictions, following Standard Model expectations, indicate that the quantity A is approximately a few times 10^{-5}; however, there is considerable uncertainty on this number and some authors find values larger than 10^{-4}. The main uncertainty arises from the need to estimate (rather than compute) certain hadronic matrix elements.

A post-workshop literature search indicates that besides the standard model level of anticipated CP violation in the hyperon system, an important class of non-standard model CP tests which are untested in the kaon sector, will be probed in hyperon decay studies[4]. Here, the benchmark of only 10^{-4} in the paramter A is already very important.

In our proposed experiment, $\overline{\Lambda}\Lambda$ pairs are formed in single events following proton-antiproton annihilation. The emitted hyperons are found to be polarized which is a necessary condition to extract the decay angular distributions. Using the extensive knowledge of the $\overline{p}p \to \overline{\Lambda}\Lambda$ reaction provided by the PS185 Collaboration at LEAR, we know many important characteristics from which we are able to optimize parameters (example, momentum of the reaction, acceptance) and therefore make very reliable count rate and sensitivity estimates. The proposed experiment would utilize an intense 1.65 GeV/c antiproton beam. Here the $\overline{\Lambda}\Lambda$ cross section is nearly a maximum and no other hyperon-antihyperon thresholds have been opened. The events are cleanly recognized as 2 V^0 patterns. Note, that only events with a fully reconstructed Λ and $\overline{\Lambda}$ are analyzed. Systematic errors appear *only in second order.*

In 1992, some of us participated in an extensive Study Group to investigate the possibility of mounting a competitive CP violation experiment based on the quantity A for the lambda-antilambda system. In our report[5], we presented the detailed case on how to achieve a 10^{-4} measurement of A with a running time of 10^7 beam-on seconds. To mount the experiment, a custom antiproton storage ring, coupled with an intense hydrogen jet

[4] See for example "CP violation in $\Lambda \to p\pi$ beyond the Standard Model, hep-ph/9508411

[5] CERN/SPSLC 92-19

target, are required in order to achieve the desired luminosity of $6.6 \times 10^{31} cm^{-1}s^{-1}$. This was not available at LEAR; with a major upgrade of LEAR, the right storage ring could be made, however the antiproton intensities would remain well below the goal. At FNAL, technical obstacles for extracting antiprotons from the existing antiproton accumulator into a dedicated ring raised the cost of such a project to an insurmountable height. Additionally, the full antiproton flux is directed to the collider program which has priority. During the workshop, our discussions with machine experts indicated that here at BNL such a custom ring could be built for a modest cost and could be fed continuously from the Booster in order to achieve luminosities at or above the Study Group goal.

In passing, we remark that a hyperon-antihyperon CP experiment is being mounted for for the present (and last) fixed-target run at FNAL. The collaboration aims at the same sensitivity as we propose here, however they go about it in a very different and complementary manner. The will study alternatively the decay chains of either cascade hyperons or anticascade hyperons, both produced with zero polarization. There is one very important difference in their method compared to ours. Ours has *no* first-order systematic errors based on acceptances or any other issues. Their method contains inherent first-order systematic considerations, since they are sensitive even at the level of acceptance for particles compared to antiparticles (our method is not sensitive to such effects).

With such promise, we are ready to study further this proposition. We believe that the potential to probe *direct* CP violation is very compelling physics. Clearly it will take a considerable effort to advance our ideas toward a pre-proposal level. With encouragement from BNL, many of us are eager to take on this challenge.

6 Conclusion

The Antiproton Working Group succeeded in generating excitement for possibilities for a world-class, exclusive antiproton program at Brookhaven National Lab. Many details have to be studied in order to make both technical and financial estimates beyond those presented at the Workshop conclusion. However, if our preliminary estimates are right, all or part of the physics program sketched above could be obtained at a very reasonable ratio of physics to dollars spent. We urge the Laboratory to provide technical assistence in further exploring the many machine-related aspects of what we propose. We believe the physics is compelling and the Brookhaven is the place to carry it out.

Report from the "Exclusive Scattering and Polarization" Subgroup.

S. Heppelmann

Subgroup Members:
E. Minor, D. Zalov, M. Strikman, A. Carroll, Y. Makdisi, W. Guryn, L. Trueman, Y. Panebratsev, M. Tokarev, R. Badalian, E. Piasetsky, Itamar Navon, G. Miller C. Perdrisat, J. Ralston, M. Bachman

Abstract

This report describes the conclusions of the AGS2000 subgroup on Exclusive Scattering and Polarization. We propose an experiment that will measure the initial and final state interactions in (p,2p)D scattering for both transverse spin aligned and anti-aligned initial states. The proposed modification of the E850 apparatus for this experiment will include polarized nuclear (deuteron) beams, a polarized proton target (frozen spin) and a forward fragmentation calorimeter.

Introduction

This document describes an AGS experiment to measure the double transverse spin asymmetry in the initial/final state interactions associated with the reaction $P + D \Rightarrow P + P + X$ in the region of kinematics with a hard (high p_t) subprocess $P + P \Rightarrow P + P$. The experiment described here will investigate a possible relationship between three mysterious phenomena in exclusive scattering experiments. The phenomena are:

1. **The energy dependence of the 90° pp elastic cross section**[1]. It is known that the pp cross section has an energy dependence given by

$$\frac{d\sigma}{dt} = R(s)\, s^{-10}.$$

The function *R(s)* represents the deviation[2] from a pure power law and variation of as much as a factor of two are observed in the incident energy range up to 20 GeV. The predicted power is 10 for the leading twist contributions to hard scattering between three quark objects. Independent scattering of quarks leads to a smaller predicted power of 8. The radiative corrections to the exclusive process tend to eliminate independent scattering amplitudes and increase the power back toward 10. It is the s^{-10} behavior which corresponds to short distance scattering and for which Color Transparency phenomena is expected. Deviations from power law form are such that in the 10 to 12 GeV energy range, *R(s)* is increasing rapidly. Some have suggested that new component to the pp scattering process is entering in this region.

[1] J. Ralston and B. Pire, Phys. Rev. Lett. 61, 1823 (1988).
[2] A. Hendry, Phys. Rev. D10, 2300 (1974).

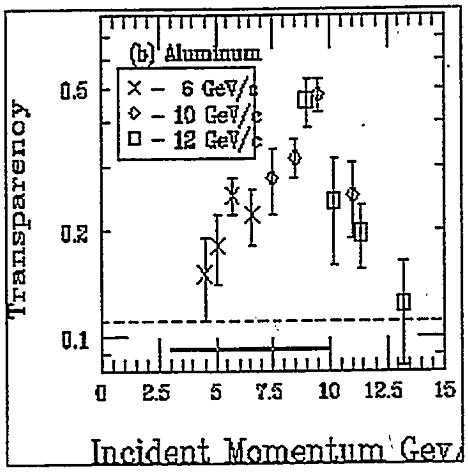

Figure 1: E834 Transparency Result

2. **The Energy Dependence of Color Transparency for 90° pp elastic scattering[3].** A dramatic reduction in nuclear transparency to pp scattering, or equivalently an increase in initial and final state interactions in (p,2p)A, is observed in the incident energy range of 10 to 12 GeV. This is well correlated with the increase in *R(s)* discussed above. One speculation is that a new component to the scattering amplitude enters in this energy range and that this component is responsible for the increase in initial and final state interactions.

3. **The onset of a large spin asymmetry (A_{NN}) in 90° pp elastic scattering[4].** It is found that there is large and unexpected asymmetry in the cross section between spin aligned $\sigma^{\Uparrow\Uparrow}$ and anti-aligned $\sigma^{\Uparrow\Downarrow}$ scattering in pp elastic scattering near incident energy of 10-12 GeV. At lower energy (5 to 10 GeV), the $\sigma^{\Uparrow\Uparrow}$ and $\sigma^{\Uparrow\Downarrow}$ cross sections are about equal (to within 20%), which is consistent with the expectation from perturbative QCD. At 12 GeV, $\sigma^{\Uparrow\Uparrow}$ is 4 times greater than $\sigma^{\Uparrow\Downarrow}$. In terms of the change in *R(s)* in this region, it is found that all of the increase in *R(s)* in this region comes from the increase in $\sigma^{\Uparrow\Uparrow}$ component. It has also been noted that if the extra strength in the $\sigma^{\Uparrow\Uparrow}$ process is associated with increased initial and final state interaction probability, that same component could well account for all the additional initial and final state interaction (or reduction of Transparency) observed in spin averaged measurements.

The proposed experiment will remeasure A_{NN}, the double transverse spin asymmetry, in pp scattering with the collisions involving a beam of polarized Deuterons (10-12 GeV/nucleon) on a polarized Hydrogen target. A_{NN} is defined in terms of the two cross sections $\sigma^{\Uparrow\Uparrow}$ and $\sigma^{\Uparrow\Downarrow}$,

$$A_{NN} = \frac{\sigma^{\Uparrow\Uparrow} - \sigma^{\Uparrow\Downarrow}}{\sigma^{\Uparrow\Uparrow} + \sigma^{\Uparrow\Downarrow}}.$$

With a Deuteron beam, the measurement involves the hard scattering between the spin aligned proton in the spin aligned Deuteron and the target proton. This pp⇒pp exclusive hard subprocess is observed in both the exclusive breakup of the Deuteron $P + D \Rightarrow P + P + N$, and the inclusive breakup $P + D \Rightarrow P + P + N$+X.

One consequence of final state interactions will be to reduce the exclusive channel and increase the cross section for inclusive breakup. Another consequences of final state interactions will be a modification of the distribution of momentum observed between the high P_t proton and neutron from the Deuteron[5]. In this proposed experiment as shown in Figure 2, a distributions in $\mathbf{k} = (\mathbf{P}_N) - (\mathbf{P}_1 + \mathbf{P}_2)$ will be measured for both the aligned and anti-aligned spin combinations of proton and Deuteron spin. We in particular emphasize the transverse components $\mathbf{k}_T$ of this momentum.

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[3] A. Carroll et. al.,Phys. Rev Lett. 61, 1698 (1988).
[4] D. Crabb et. al., Phys. Rev. Lett. 41, 1257 (1978).
[5] L. Frankfurt et. al., Phys. Lett. B369, 201 (1996).

The transverse component perpendicular to the hard scattering plane k_y is easiest to measure accurately. In general, the observed shape of the k_y distributions can be traced to two sources:

1. The internal wave function of the Deuteron.
2. The transverse momentum from final state interactions.

In the region above 200 MeV/c the contribution from final state interactions is expected to be large compared to the part due to the Deuteron wave function. Thus while the initial/final state interactions are in general small for a Deuteron, in selected regions of kinematics, we expect the final state interaction effects to dominate.

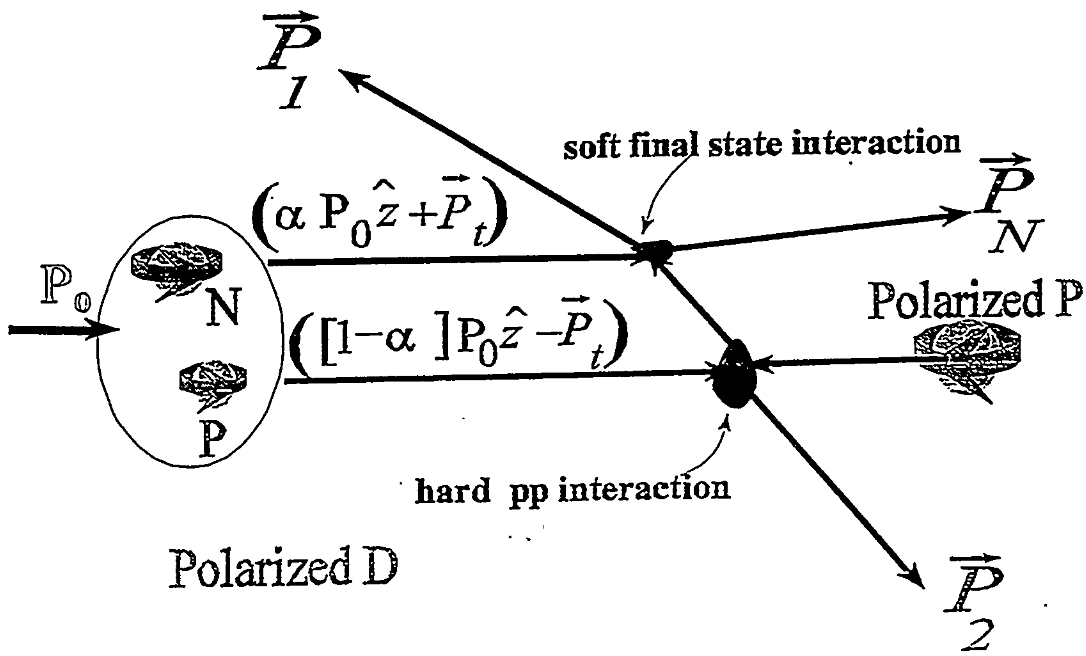

Figure 2

The Kinematics hard pp scattering in Deuteron with soft final state interaction. The coordinate system is defined by the Deuteron Beam direction z and with the hard scatter in the x-z plane.

The basic hypothesis of this experiment is the proposition that the decreased transparency seen in pp hard scattering in the 10 to 12 GeV region is related to a new interaction mechanism which also contributes to the measured excess in $\sigma^{\Uparrow\Uparrow}$ over $\sigma^{\Uparrow\Downarrow}$. Various mechanisms of this kind have been proposed[6]. The measurement will be a comparison of the distributions $\frac{d\sigma^{\Uparrow\Uparrow}}{dP_y}(P_y)$ relative to $\frac{d\sigma^{\Uparrow\Downarrow}}{dP_y}(P_y)$. The hypothesis leads to the prediction that the high momentum component (P_y > 200 MeV/c) will be many times larger for collisions between spin aligned than for spin nonaligned initial states.

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[6] S. Brodsky and G. de Teramond, Phys. Rev. Lett. 60, 1924, (1988).

A positive result in this experiment will dramatically demonstrate the basic principle of Color Transparency in pp exclusive scattering while establishing a definitive connection between the large spin effects in pp scattering with Color Transparency phenomena. It would show that several mysterious effects in the 10 to 12 GeV region of pp hard scattering are manifestations of a single new phenomena.

Experimental Procedure.

The experiment will utilize the E850 detector[7] which has been designed to trigger on and measure the rare hard pp quasi-elastic scatters in nuclear targets. The intent of E850 is to measure Color Transparency related phenomena by observing deviations from Glauber model predictions in the initial and final state interactions associated with these hard events. The detector triggers on back to back pairs of high P_T particles. The energy resolution associated with the measurement of the pair of high P_T particles will be about 200 MeV/c for incident beams of 10-12 GeV. The low energy breakup of the nucleus is only partially observed in the E850 detector.

The new experiment will require a polarized proton frozen spin target and a polarized Deuteron beam. By using a Deuteron beam rather than a Deuteron target, the neutron from the breakup is produced at high energy, around 10 GeV, and is observable and measurable in a forward fragmentation tracker/calorimeter of modest size, about 30 cm radius. The requirement that the Deuteron be fully reconstructed will assure that the Deuteron fragments into a proton and a neutron.

Using results from the E850 apparatus, it is estimated that the new experiment would observe about 10K events per month. This estimate requires the following:

1. 10 cm long, frozen spin hydrogen target with 50% polarization.
2. Deuteron beam with 50% polarization, 10^8 per spill.
3. Forward Tracking neutron calorimeter inside the magntic pole piece.

Meeting these requirements, a decisive measurement could be made in one month. Theorists in our subgroup have made preliminary estimates that above 200 MeV/c, the difference in the spin aligned and spin anti-aligned momentum spectrum should be over a factor of five. We will collect several hundred events in this kinematic region for both spin alignments in one month.

Required New Facilities or Equipment

The cost of this experiment has not been fully estimated but will involve three categories.

- The first is an upgrade of the C1 beamline for transporting an equivalent proton energy of 24 GeV.
- The second is the construction of a polarized frozen spin hydrogen target. This can piggy back on the ongoing LEGS project which will design a similar target.
- The third is the development of a hadronic tracking calorimeter for detection of the Neutron. This calorimeter would be designed to track the hadronic shower with a position resolution of about 2 cm. The shower tracker would be in the pole piece of the E850 detector and would have an "active area" radius of 30 cm.

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[7] J. Y. Wu et. al., Nucl. Instr. Meth., A394, 183 (1994).

Hypernuclei and Baryon Interactions

Since the late 1970's, the study of hyperons embedded in nuclear matter has occupied the attention of nuclear physicists at the AGS and at KEK. These laboratories have been at the focus of the world's research into nuclei containing hyperons. The continuing research program and this workshop have brought these groups even closer together, and as a result, they have developed plans for an orderly exploitation of this field through the beginning of the 21st century and beyond.

The baryon-baryon force is responsible for the structure of strange matter, and any textbook on strange matter will have hypernuclei in its first chapter. The keystone is the study of the baryon-baryon forces. Since we lack hyperon beams, the only practical way to study the fundamental force is to use the hypernucleus as a laboratory in which to contain the interactions. In the S=-1 domain these interactions are the ΛN and the ΣN. The hyperon-hyperon arena can be accessed with S=-2 hypernuclei. Key issues in the fundamental interactions are the SU(3) symmetry breaking through the ΛN-ΣN and the $\Lambda\Lambda$-Ξ-N mixing, and the relation between the quark-gluon and boson exchange descriptions of the forces. Using the strangeness exchanging reactions, the spin-spin and spin-orbit force, charge symmetry breaking, the weak interaction among baryons, and the special dynamical symmetries allowed by the absence of Pauli repulsion are all topics especially amenable to study.

For doubly-strange systems, the possibility of examining the $\Lambda\Lambda$ force is the ultimate goal; the subsidiary, but related goal, is to answer the question: Is there a spectroscopy of Ξ hypernuclei? The existence of $\Lambda\Lambda$ hypernuclei bears on the possibility of the existence of the H-dibaryon. The work on strange systems at the AGS is closely connected to research on kaon production at CEBAF and with multi-steange matters studies with RHIC.

The main conclusion of the workshop is that much of the key instrumentation needed to pursue these topics is already in place at the AGS, or KEK. There are now plans to locate much of the KEK devices at the AGS. The one category which needs further development is the doubly strange nuclear systems. We assert that *the key device which needs yet to be developed is a spectrometer for the measurement of doubly-strange systems, referred to herein as the "S2S" spectrometer.*

$\Lambda\Lambda$ Hypernuclei

The new and exciting world of $\Lambda\Lambda$ hypernuclei has already been entered at the AGS through the running on E885. This experiment produces stopping Ξ's in a diamond carbon target, and the capture of the Ξ's on carbon to form a doubly-strange nuclear system is observed through detection of the decay products in a scintillating fiber array, and the decay neutrons in a neutron array with high acceptance. An outgrowth of the previous H dibaryon searches in E813 and

E836, the observation of $\Lambda\Lambda$'s will place severe constraints on the mass of this dibaryon.

The NMS–A New Tool for Hypernuclei

In place and taking data in the LESBII C8 line is the neutral meson spectrometer. Offering the promise of sub-MeV missing mass resolution, the NMS is currently studying states in $^{12}{}_{\Lambda}$B with the K,π^0 reaction. The ability to produce mirror hypernuclei will greatly extend the variety of hypernuclei and enhance the systematic studies of Λ systems. NMS can also be used to detect other neutral mesons, like the η, which are copiously formed in the nuclear medium through the excitation of baryon resonances in the nuclear medium.

A particularly exciting prospect with the NMS is the production of $^4{}_{\Lambda}$H, which together with its mirror $^4{}_{\Lambda}$He, can be used to isolate and compare the weak interaction amplitudes for directly testing the Δ I = 1/2 rule. *The NMS offers the opportunity of clarifying once and for all the structure of the weak interaction Hamiltonian.* We expect a proposal for this measurement to be made soon.

Kaonic X-Rays

The observation of kaonic X-rays from targets of hydrogen and deuterium gives information on the threshold interaction of the $\bar{K}$N. From these measurements we can obtain the I=0 and I=1 scattering lengths, providing sufficient statistical accuracy is attained. At the K3 beam of KEK, the feasibility of the experiment has been demonstrated. Tagging of the stopped kaons is established through detection of the decay pions. For precise scattering length determinations this experiment will be moved to the AGS, and will obtain an order-of-magnitude improvement in statistics.

Hypernuclear γ Spectroscopy with the Germanium Ball

The spin dependence of the YN interactions is at poorly constrained by the available data, and almost nothing is known about the tensor component. For obtaining that information what is needed is a large acceptance, high resolution, γ-ray spectrometer. In Japan, construction of a 14 element n-type Ge array, with an acceptance of 17 % of 4π has been started with a budget of \$1.3 million. Such a spectrometer provides 2 keV resolution, necessary for the separation of the closely spaced spin doublets characteristic of hypernuclei.

The high intensities available at the AGS make it attractive to move these detectors to the AGS, after initial tests at KEK. Three series of studies are contemplated For initial tests, the rates with a reassembled Moby Dick spectrometer at C-line are adequate for K$^-$,π reactions on P-shell targets. In a second stage, use of the ball with the NMS, accessing mirror nuclei is contemplated. In the third stage, the higher momentum of the D-line will allow the examination of spin-flip states, and the study of doubly-strange systems. This stage, requires a high acceptance (100 msr) spectrometer, referred to in this summary as the "S2S" spectrometer. *High resolution spectroscopy with a germanium ball is a key component of a hypernuclear program, and it should be pursued with vigor at the AGS in preparation for later work at the Japan Hadron Project.*

The Cylindrical Detector System

E906 will use the CDS detector to observe the sequential emission of pionic decays from double-Λ hypernuclei at the D6 beam line. The plan is to produce these doubly-strange objects in a direct K^-,K^+ reaction, which results in the production of hyperfragments. A small, but non-zero, fraction of such fragments will carry two strange quarks. Such fragments can decay by the emission of pions, whose energies are measured in CDS. CDS is a versatile out-of-beam reaction product detector, with an acceptance of 65% of 4π. With a solenoidal field of 0.5T and a FWHM of 3 MeV/c, it will be useful in a number of experiments.

YN Scattering with the CDS

The scattering among baryons plays a fundamental role in understanding how baryons interact and join to form nuclear matter. Our knowledge of the nucleon-nucleon interaction is detailed, while the analogous information in the hyperon nucleon sector is extremely sparse. Scattering data form the required input to decide among the various interaction models of such as the Nijmegen or Juelich schools.

It appears feasible to consider Λ-proton scattering with a pion beam and Ξ^--proton scattering using a kaon beam at the D6 line. With the introduction of a liquid hydrogen target, it appears feasible to study these collisions in the CDS spectrometer. *A proposal to accomplish the fundamental YN scattering studies will be submitted to the AGS PAC.*

The Spectroscopy of Doubly-Strange Nuclei with the S2S

In hypernuclear physics, the showcase experiment to lead the way into the 21st century is the attempt to establish the existence of Ξ-nuclear states. There is strong theoretical hints that such states exist because of the rather limited phase-space available for their conversion to non-strange systems. The formation will occur via the double strangeness and charge exchanging (K^-,K^+) reaction. Widths of about 2 MeV are predicted, and from a study of the major shell structure and the binding, the Ξ single particle well depth can be determined. Of special interest is their decay modes. Competing theories predict sharply different spreading and neutron decay widths for these states, and their measurement will resolve which hyperon-nucleon interaction model is to be preferred.

Much of the needed equipment for such studies is already in place at the D6 line, especially the high efficiency neutron detector array. With the advent of the Germanium Ball (see above), γ decay studies on S=-2 systems could be carried out, opening a wholly new era of high resolution studies on the doubly strange systems, including $\Lambda\Lambda$'s and Ξ's.

The key element which is yet to be provided is a high resolution ($\sim$2 MeV), high acceptance ($\sim$ 100 msr) spectrometer matched to the 2.0 GeV/c beam line, replacing the present 48D48 open, non-focusing magnet system. With such a spectrometer, and a modest proton on target irradiation of 10 Tp, a reasonable count total of several thousand in a specified state in $^{12}_{\Xi}$Be would result from a 1000 hour experiment.

Fortunately, a design for a circular pole shape superconductor magnet, with 5 T over a 50 cm gap is already being developed for another AGS experiment. A slightly scaled up version of such a magnet would be ideal for the S2S (or strangeness 2 spectrometer). *We propose a detailed study of such a design, with appropriate cost estimates, as a goal for the AGS and the JHP in the 21st century.* The working group members, in consensus, have adopted this as our main recommendation for the AGS2000 workshop.

This device, with the other instrumentation mentioned above, and with the devoted efforts of the hypernuclear community, would ensure a solid research base as we enter the 21st century and the world of the JHP.

3 PART SUMMARY OF

HIGH BARYON DENSITY WORKING GROUP

1. Focus of the Group

The group focused on the design of an upgrade for E-864 which would allow the measurement of particles produced by the Au-Au collisions that a) are short-lived (hyperon lifetimes) or b) produced over a large range of (space) angle.

The basic approach of the upgrade design is to replace the front end of E-864 with a new system consisting of a set of Time Projection Chambers. The design is arranged so that the baryons (and some of the kaons) that emerge from the front end are matched as well as possible to the existing, powerful downstream spectrometer of E-864.

To match into downstream 864 an additional magnet beyond the second magnet (M2) already present in E-864 may be needed. This is not shown in the work reported here.

2. Basic Experimental "Architecture" of the New Upgrade

We have chosen the TPC technology because it is the only one with the pattern recognition power to identify and measure the large number of tracks produced in an Au-Au collision at AGS energy.

The maximum rate of interactions which such a system can, in principle utilize, is set by the drift time of the ionization electrons in the TPC. As will be shown, the maximum drift distance is 30 cm. We assume that we will achieve a drift velocity of 5 cm/ns so $6\mu s$ is the needed time between events. We thus take 10^5 interactions per second as our maximum useable rate.

Figures 1,2 show the dimensions and the configuration arrived at during the workshop. Figure 3 shows a (highly!) schematic depiction of one of the six TPC's. As can be noted, $\vec{B}$ and the drift field $\vec{E}$ are parallel.

3. Feasibility of the TPC Approach

We have gone through a "first pass" evaluation of this system from a number of points of view:

a) two track resolution needed in the TPC

b) resolution required for the physics goals

c) occupancy problems in the TPC

d) D/A requirements

The first 3 concerns appear to be met by current TPC technology. (We have benefited from conversations with physicists involved in the EOS TPC and the Star TPC. At present, it appears that the D/A requirements to work with an interaction rate of 10^5 with a recording rate of 100 Hz are something like one order of magnitude more severe than, for example, is provided by the EOS system now at BNL. Promising direct for solving this are "in view".

4. Physics Potential

The following physics topics appear to be accessible, as noted, when this upgrade is operational. These utilize the powerful downstream 864 spectrometer as well as the TPC system.

a) Measurement of $\Lambda, \Sigma^+, \Sigma^-, \Xi^-, \Omega^-$ fluxes produced in Au-Au collision at 11.6 GeV/c per nuclei.

b) Measurement of fluxes $\overline{\Lambda}, \overline{\Sigma}^+, \overline{\Sigma}^-, \overline{\Xi}^-$ produced in 11.6 A GeV Au-Au collisions.

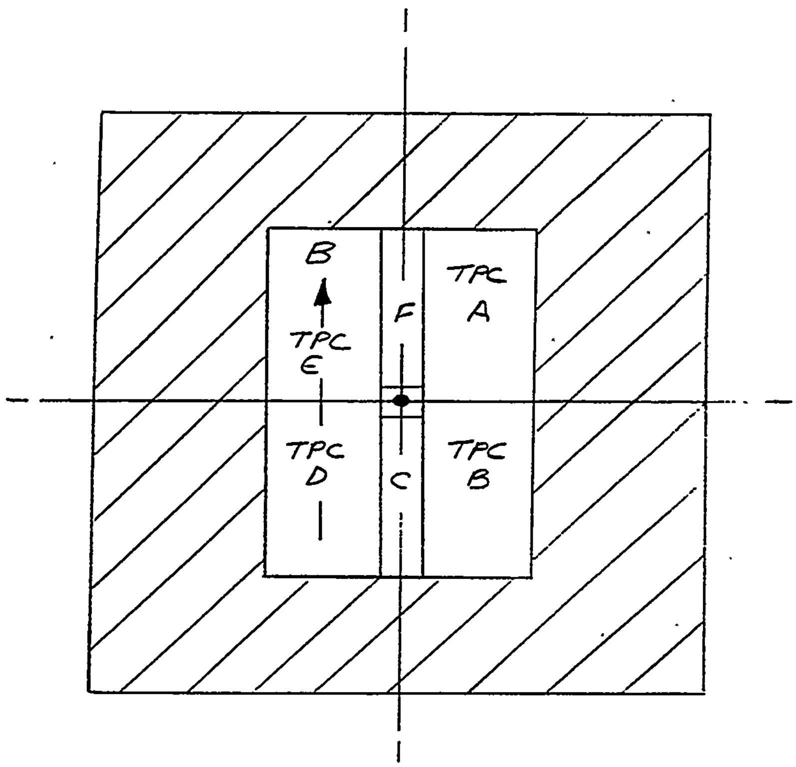
c) Measurement of multiply strange hyperfragments up to and including $\Lambda\Lambda^6 He$. The interesting $\Xi\Lambda\Lambda^7 He$ appears to be on the edge of this system's capability if conservative coalescence estimates are used for its production.

d) Search for strangeness with short (hyperonic) lifetimes. This is complementary to E864 which requires (approx) 50 ns. Limits of 10^{-7} per central at collision can be reached in one week.

e) Search for the "strangeness distillation" process.

f) Study of the N*. The production, mass, width of the N* can be studied in detail. In particular the possible mass shifts due to medium effects can be studied.

E-864 NEW FRONT END

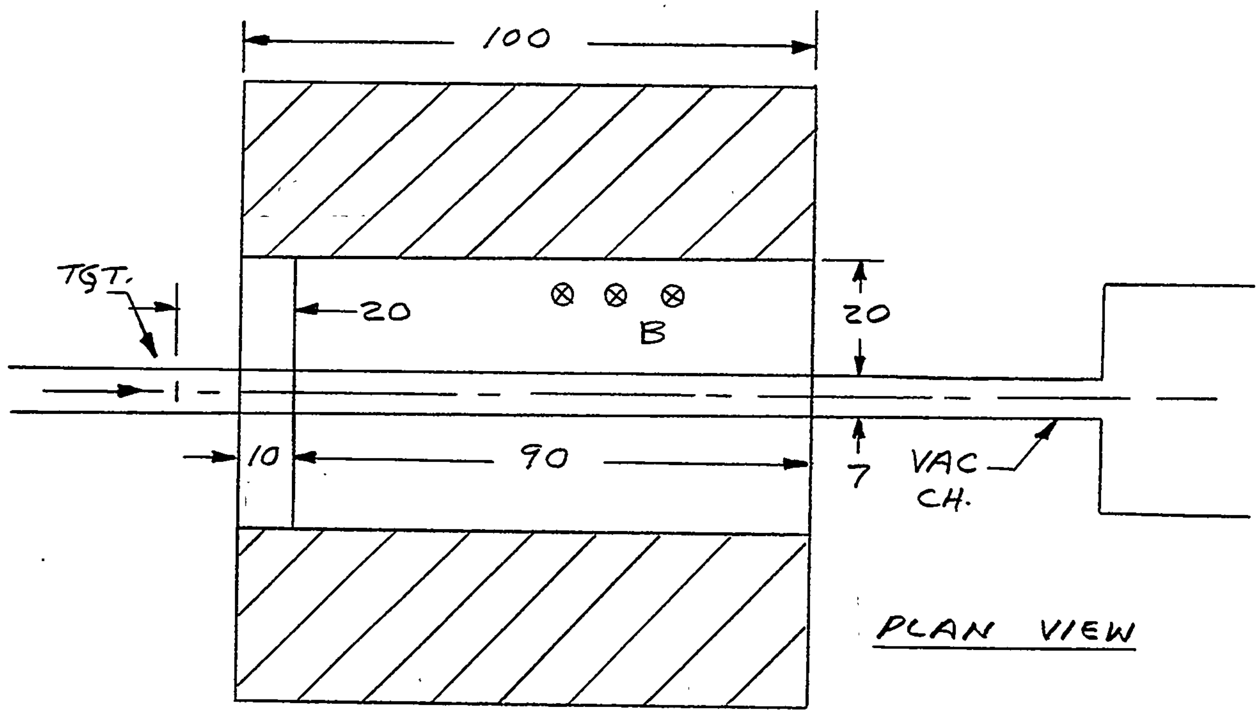


BEAM'S EYE VIEW

B = 10 Kg.

Fig. 1

ALL DIM'S. CM.



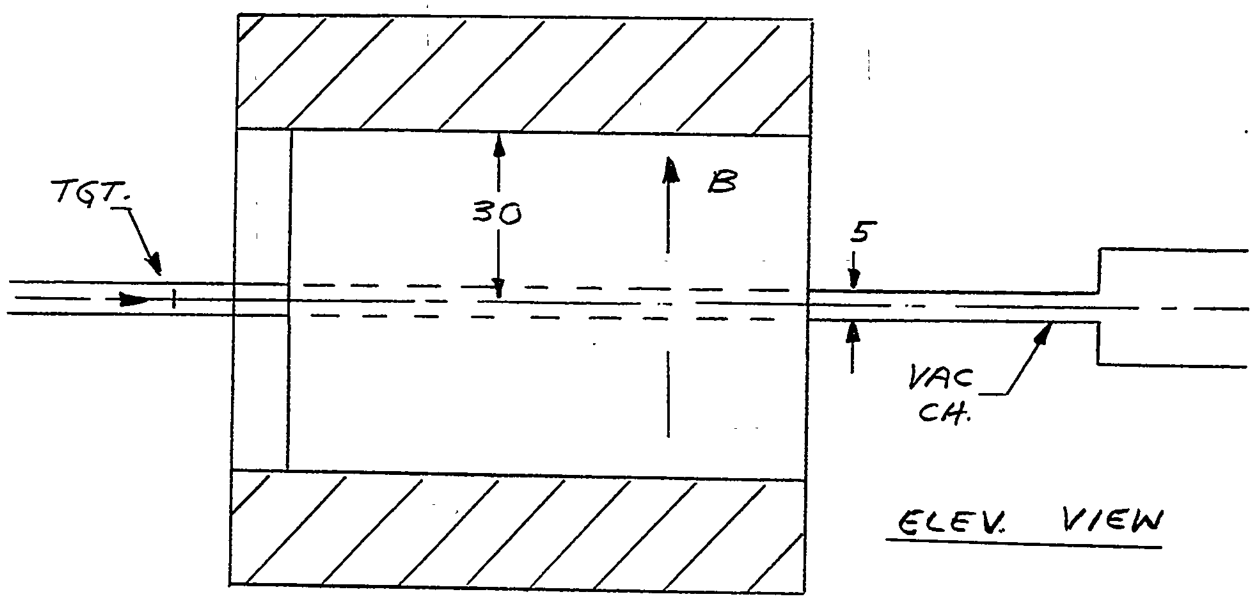
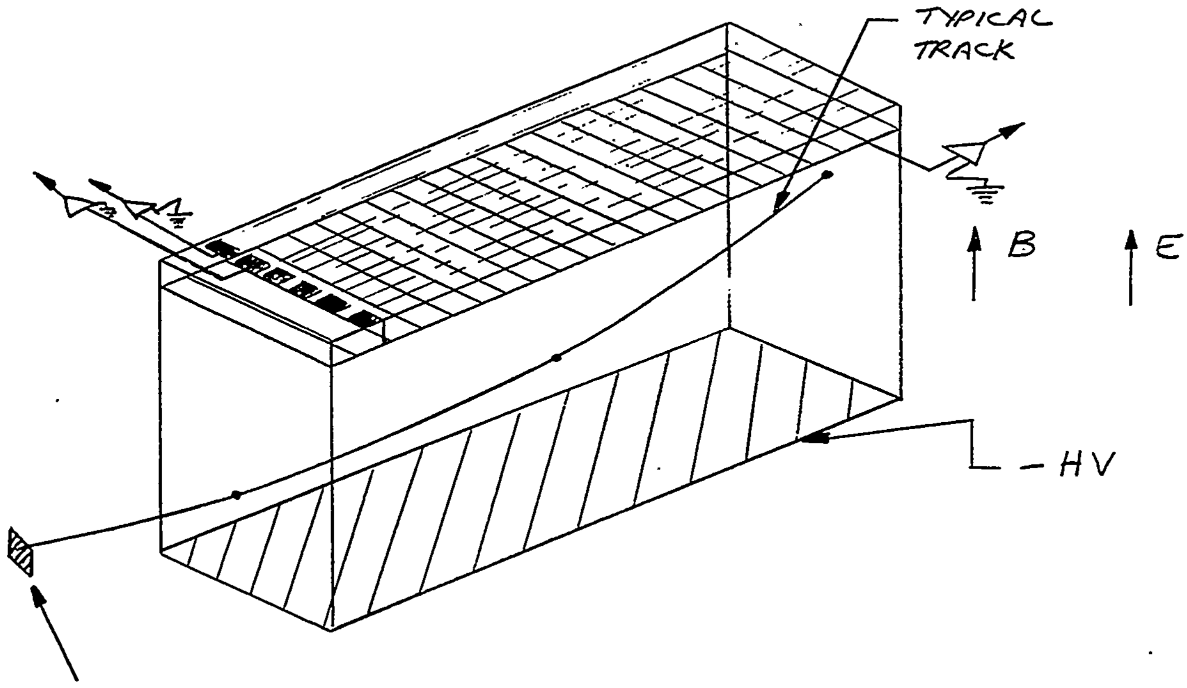


FiG. 2



TPCA
SCHEMATIC

Fig. 3

Experiment to measure the EDM of Muon

Yannis Semertzidis, Brookhaven National Laboratory

Francis J.M. Farley, Yale University

Donald Lazarus, William Morse, Brookhaven National Laboratory

B.L.Roberts, Boston University

June 5, 1996

The $(g-2)$ angular precession frequency of the muon spin relative to the momentum vector in combined vertical magnetic field B_0 and horizontal electric field E_0 is

$$\omega_a = [aB_0 + (\frac{1}{\gamma^2 - 1} - a)\frac{\beta E_0}{c}](e/mc) \tag{1}$$

where $a = (g-2)/2$ is the muon anomalous magnetic moment. To measure the electric dipole moment (edm) it is proposed to use a large radial electric field E_0 so that ω_a is reduced to zero. The muons then keep their forward polarization with no horizontal precession.

In the rest frame there is a horizontal electric field $E^* = \gamma\beta B$ induced by the Lorentz transformation. If there is an edm of magnitude $\eta \times (eh/4\pi mc) = \eta \times 0.93 \times 10^{-13}$ e $\cdot$ cm, then the spin will precess in the vertical plane at angular velocity

$$\omega_e = \eta\beta B_0(e/mc) \tag{2}$$

(The factor γ is eliminated by time dilation when we transform back to the laboratory frame).

If the $(g-2)$ precession is active then the combined effect is to tilt the plane of precession out of the horizontal by the small angle $\delta = \beta\eta/a$. In effect the edm starts to swing the spin out of the horizontal plane, but this effect is reversed and cancelled when the spin direction reverses because of the $(g-2)$ precession, so the overall effect is small. This has led to the current limit of about $3 \times 10^{-19}\,\mathrm{e \cdot cm}$.

But if the $(g-2)$ rotation is cancelled by applying the radial electric field, the edm precession operates on its own and the vertical angle can accumulate over many microseconds. To get $\omega_a = 0$ in 1 , we need

$$E_0/c = \frac{aB_0(\gamma^2-1)}{\beta(1-a(\gamma^2-1))} \tag{3}$$

(The term in a in the denominator will be only 0.028 in the chosen conditions and will be neglected for simplicity).

But for a fixed storage radius ρ_0

$$B_0 = \frac{\beta\gamma mc}{e\rho_0} \tag{4}$$

Therefore

$$E_0/c = \frac{amc\gamma(\gamma^2-1)}{e\rho_0} \tag{5}$$

We see that the electric field required to cancel the $(g-2)$ precession varies as γ^3. To get a good measurement we therefore need to use the highest possible electric field and thus operate at the highest available γ.

A good practical compromise occurs at kinetic energy 420MeV with $\gamma = 5$, $\beta = 0.98$, muon lifetime 11μs. For radius 711cm the magnetic field is then $B_0 = 2.4$kG and the average radial electric field required is

$$E_0 = 21\,\mathrm{kV/cm} \tag{6}$$

We will observe the vertical precession for ten lifetimes with decay electron detectors above and below the orbit. If 10^{12} decays are recorded and the asymmetry for total vertical polarization is 0.2, then we would be sensitive to a vertical angle $\theta_e = 5\mu$R. Using 2 we then find

$$\eta = \frac{\theta_e}{\beta B_0(e/mc)t} = 8 \times 10^{-10} \tag{7}$$

with $e/mc = 8.53 \times 10^8 \, \mathrm{rad\,s^{-1}\,T^{-1}}$. So the limit of sensitivity for the edm would be $8 \times 10^{-23} \, \mathrm{e \cdot cm}$.

At these fields the $(g-2)$ period would be $22\mu s$. We want to cancel the horizontal precession over the whole aperture for $100\mu s$, so the cancellation should be good everywhere to about 1 part in 400. This is not trivial because

(a) At this muon momentum ω_a varies with radius,

(b) the horizontal electric field, if made by cylindrical electrodes, will naturally decrease as $1/\rho$, and

(c) γ varies with radius.

However we can compensate at all radii if we combine a radial magnetic gradient (field coefficient n_m) with electric quadrupoles giving an effective field coefficient n_e. From eqn(3), with a little algebra, the criterion for cancellation over the whole aperture is

$$n_e = \frac{a\gamma_0^2(n_m - 2)(1 - n_m - n_e)^2}{\beta^2} \tag{8}$$

where $a\gamma_0^2/\beta^2 = 1/38$.

One of many possible solutions is $n_m = 0.25$, $n_e = -0.06$ so the effective combined gradient is $n_{eff} = 0.18$ To understand this combination note that γ increases with radius, but the radial electric field from the cylindrical electrodes decreases with radius. Further B decreases slowly with radius. In combination we need a negative value of n_e to get the correct radial dependence of E to match eqn(3) everywhere. Negative n_e is horizontally focusing; it reduces E at small radii and increases it at large radii.

Beam intensity and statistics

In this experiment we are looking for a vertical asymmetry which slowly increases with time. Any fixed asymmetry due to differences between the up and down electron detectors will not interfere.

An estimate of the number of stored muons is obtained by comparison with the predictions for the $(g-2)$ experiment.

E821 will store 2.4×10^{11} muons in 400 hours of dedicated muon injection running at 6μA AGS average current. The AGS current is expected to be 15μA by the year 2000 with tuning and barrier buckets. If the accumulator is built and the AGS power supply is upgraded to 2.5Hz, the current is anticipated to be 40μA. For E821 with a 3.1 GeV/c pion beam, 38% of the pions decay to muons from the pion selection slit at 8.7m to the pion rejection slit at 97.5m. For the 0.5 GeV/c beam 70% decay in this region. The E821 pion/muon beamline collects pions within 32mrad horizontal $\times$ 60mrad vertical with a momentum acceptance of 2% base-width, ie. 60MeV/c. The polarization is high: 97% for pion injection; somewhat less for muon injection. The flux of 0.5 GeV/c pions within this acceptance is much less than 3.1 GeV/c pions. $d^2N/dpd\Omega$ is less by a factor of about three from Hagedon and Randft, and dp is less by the ratio of 0.5 to 3.1.

Change	Intensity Factor
15μA (barrier buckets)	2.5
40μA (accumulator)	6.7
0.5 GeV/c Pions	0.06
Muon Decays	1.8

The number of stored muons is then down to 0.70 compared with (g-2) even with the AGS accumulator. What is needed is a much larger acceptance beamline with matching acceptance in the storage ring maintaining the polarization. Note that in the $(g-2)$ experiment the acceptance is a good match to the rate capabilities of the detector (primarily systematic shifts in timing at high rates) and the weak electrostatic focusing at the magic gamma necessary to know the magnetic field at the required high accuracy. But for the new edm measurement different criteria apply.

We conclude that with a weak focusing ring and without the accumulator we will only be able to process about 6×10^{10} decay electrons in a 400 hour run, so the limit on the muon edm would be $3 \times 10^{-22}\, e \cdot \mathrm{cm}$. We are studying the possibility of increasing the acceptance of the ring by using strong focusing and adapting the muon decay channel to correspond. This might be able to increase the stored intensity by a factor of 100-300, so that about 2×10^{13} decays could be recorded in 400 hours. Then the edm might be measured to order $2 \times 10^{-23}\,e \cdot cm$. A further improvement by raising the electric field by a factor of 2, and using a lithium lens at the production target to collect more pions are under investigation. In combination to running for longer than 400 hours might bring us well into the $10^{-24}\,e \cdot cm$ region.

Note that by increasing the energy of the pions entering the decay channel we can select muons from backward decay with polarization reversed. The up/down asymmetry generated by the edm should then be opposite. Although the beam intensity would be smaller, this is a good way to cancel some of the residual systematic errors.

An AGS2000 White Paper

A Direct Measurement of the Muon Neutrino Mass by Pion Decay in Flight in the g-2 Ring

P. Cushman, University of Minnesota

Francis J.M. Farley, Yale University

Klaus Jungmann, University of Heidelberg

P. Nemethy, New York University

B.L. Roberts, Boston University

William M. Morse, Yannis K. Semertzidis, Brookhaven National Laboratory

June 6, 1996

1 Introduction

It appears possible to improve substantially on the current sensitivity for the mass m_ν of the muon neutrino by measuring pion decay in flight in the E821 (g-2) muon storage ring. Pions of 3 GeV are injected into a 14 meter diameter storage ring with a B-field of 1.5 T. In the subsequent two-body decay $\pi \rightarrow \nu_\mu \mu$, the presence of a massive neutrino would result in a smaller than expected momentum for the decay muon. Measuring the difference in momenta $p_\pi - p_\mu$ for forward going muons gives the neutrino momentum, from which the mass can be extracted. The neutrino mass determination then becomes almost independent of the error in the pion and muon masses.

$$m_\nu^2 = [\sqrt{p_\mu^2 + m_\mu^2} - \sqrt{p_\pi^2 + m_\pi^2}]^2 - p_\nu^2.$$

At present, the limit on the muon neutrino mass is 160 keV (CL=0.9)[1], which comes from a PSI experiment using stopping pions. Experiments where the pion is brought to rest rely on a very accurate measurement of the momentum of the daughter muon, from which the neutrino mass is inferred using the relation

$$p_\mu^2 + m_\mu^2 = (m_\pi^2 + m_\mu^2 - m_\nu^2)^2/4m_\pi^2.$$

The other ingredient in the formula is the mass of the pion, which contributes about equally to Δm_ν^2. Uncertainties in the mass of the pion are therefore the dominant limiting factor in improving the sensitivity of this type of experiment. Uncertainties in the muon mass are a much less significant contribution. The upper limit of 160 keV is calculated by assigning the probability function to zero for $m_\nu^2 < 0$, since plugging directly in the values in the formula above and using the measured pion mass yields a negative value for m_ν^2.

The Particle Data Book value for the pion mass is heavily weighted by one experiment [2] which is based on X-rays from pionic atoms (4f→3d transitions in ^{24}Mg). In the last couple years, the Jeckelmann pionic X-ray spectrum has been reanalyzed [3], resulting in two solutions for the pion mass, depending on whether the strongest component in the 4f-3d transition is assumed to be in the presence of one or two K-electrons. With the larger pion mass (2 K-electrons), Assamagan et al. find $m_\nu^2 = -0.022 \pm 0.023 MeV^2$, consistent with zero. Since the smaller pion mass still gives a negative mass-squared term by six standard deviations, and since earlier pion mass experiments (e.g. [4]) which observed pionic X-rays in other materials (e.g. phosphorus and titanium) are consistent with the smaller mass, there still may be a model-dependent element in this analysis. Therefore, although we believe that an order of magnitude improvement in the current limit is possible, even a first stage measurement which confirms the present limit would be interesting, as it does NOT depend heavily on the pion mass. The uncertainty quoted on the preferred pion mass solution corresponds to a 5 keV uncertainty in the neutrino mass as determined from 3 GeV pions in flight. This is acceptable if our goal is to measure the momentum difference $\Delta p = p_\mu - p_\pi$ with a resolution of $\frac{\delta \Delta p}{(p_\mu + p_\pi)/2} \sim 10^{-7}$ which corresponds to a neutrino mass uncertainty of 30 keV.

2 Experimental Method

2.1 Measurement in the Spatial Domain

We examined both the temporal domain and the spatial domain to establish the best experimental method. The most accessible using current experimental techniques appears to be the spatial domain. The general philosophy is to make a precise position measurement of the incoming pion and another measurement one turn later of either the undecayed pion or the daughter muon. Pions which do not decay, end up back at the same position on the detector from which they started NO MATTER what their initial momentum and angle, whereas the daughter muons cover a range of positions. The outer edge of the muon distribution is sensitive to the neutrino mass. Such a precise measurement must have no multiple scattering or energy loss, thus no intermediate detectors, and must be made a particle at a time. This requires a slow extracted beam from the AGS and considerable reduction in beam emittance.

In practice, we cannot do the simple one-turn experiment using a single detector because the particles will hit the inflector before they make a complete circuit. The pions' initial radial position x_1 will therefore be recorded by a detector S1. The undecayed pions will be refocused to a nondispersive image at a point before the inflector where their radial position x_2 will be measured by a second detector S2. The optics of the g-2 magnet must be adjusted to give a precise mapping of S1 onto S2 with a resolution of order 1 μ (See Beam Optics section below for details).

If the pions decay in flight between S1 and S2, then the muons will hit S2 at a range of positions. For muons which decay in the forward direction ($\theta_{decay} = 0$):

$$\frac{\Delta D}{D.} = \frac{p_\mu - p_\pi}{p_\pi} = \frac{p_0}{\beta_\pi(1+\beta_\pi)\gamma_\pi^2 m_\pi}[1 - \frac{\beta_\pi(1+\beta_\pi)\gamma_\pi^2 m_\nu^2}{2p_0^2}] \tag{1}$$

where D is the diameter of the pion orbit, $(D+\Delta D)$ is the diameter of the muon orbit and p_0 is $\pi - \mu$ decay momentum in the pion rest frame. If the decay occurs half way between S1 and S2, then the maximum muon offset $(x_\mu - x_1)$ is clearly equal to ΔD. It turns out that this is the maximum possible value, wherever the decay occurs, and so ΔD is the end point of the muon spectrum. Let the position of the muon hit in S2 be x_μ, then the distribution defined by $(x_\mu - x_1)$ is continuous up to +3.027 mm, at which point it ends sharply. The position of this end point is sensitive to the neutrino mass m_ν, but relatively insensitive to the uncertainty in the pion mass. From Eq. 1 we obtain the displacement of the end point due to the neutrino mass,

$$\frac{\delta D}{D} = \frac{-m_\nu^2}{2p_0 m_\pi} \tag{2}$$

The current limit of m_ν=160 keV corresponds to a $\delta D = 43.1\mu m$, while $1\mu m$ corresponds to m_ν = 24 keV.

For a realistic range of pion momenta and angles, the edge of the distribution is smeared somewhat. In order to understand how this would affect the sensitivity achievable by this experiment, a simple Monte Carlo, corresponding to a uniform B-field with a central trajectory of 7 meter radius for 3 GeV pions was written. The momentum bite is Gaussian with a sigma of .1% and the angular variation is Gaussian ($\sigma = 1mr$). Particle orbits are killed if they extend beyond the 9 cm storage region. Figure 1 shows the radial position of the decay muons, x_μ, in meters versus the decay angle (THET0) in the center of mass (inward decays are labeled as negative THET0). Undecayed pions will all hit at x_μ=7 meters. Forward decay angles only contribute to the outer radial positions, whereas large decay angles contribute a huge swath, including positions to the outside and inside of the pion peak. In figure 2, a blowup of the outermost region reveals that only very forward decays are responsible for the sharp edge at the endpoint. Figure 3 shows just how sharp we can expect the radial distribution ($x_\mu - x_1$) in millimeters to be, if the momentum distribution is Gaussian, as described above. The dashed line is for a neutrino mass of 160 keV.

Since we don't actually know what the momentum distribution will be, this uncertainty will limit our sensitivity. To know by how much requires a detailed study, but a first glance at the difference between a delta function, a Gaussian distribution of $\sigma = .1\%$, and a flat distribution with a $\delta p/p = 0.1\%$ endpoint indicates that this may be as much as 5 μm. The flat distribution is the third curve (dotted) on figure 3, yielding a sharper distribution than the Gaussian. The solution is to limit the momentum spread by a collimating veto counter at the halfway point. Further information could be obtained by actually measuring the radial distribution (x, x') in a separate run using a set of chambers in the ring.

2.2 Beam Optics and Detector Details

Since this experiment depends on measuring the particle position one particle at a time, slow extracted beam must be provided to the g-2 storage ring. Presently, only bunched beam is available. The E821 beam calculations give 10^8 positive pions at the end of the inflector magnet for 7.5×10^{12} protons on target, or one bunch from the AGS. The FWHM pion beam phase space parameters at the end of the inflector magnet are: 53mm, 6mrad (vertical), 14mm, 8mrad (horizontal). The E821 muon beam defining collimators are 90 mm diameter. These parameters are optimized to provide the high intensity beam required for E821. Since the neutrino mass experiment cannot take more than 10^6 particles per second, the beam emittance can be drastically limited. This has the additional advantage that it limits the region over which the B-field must be uniform and prevents any scattering from apertures or walls.

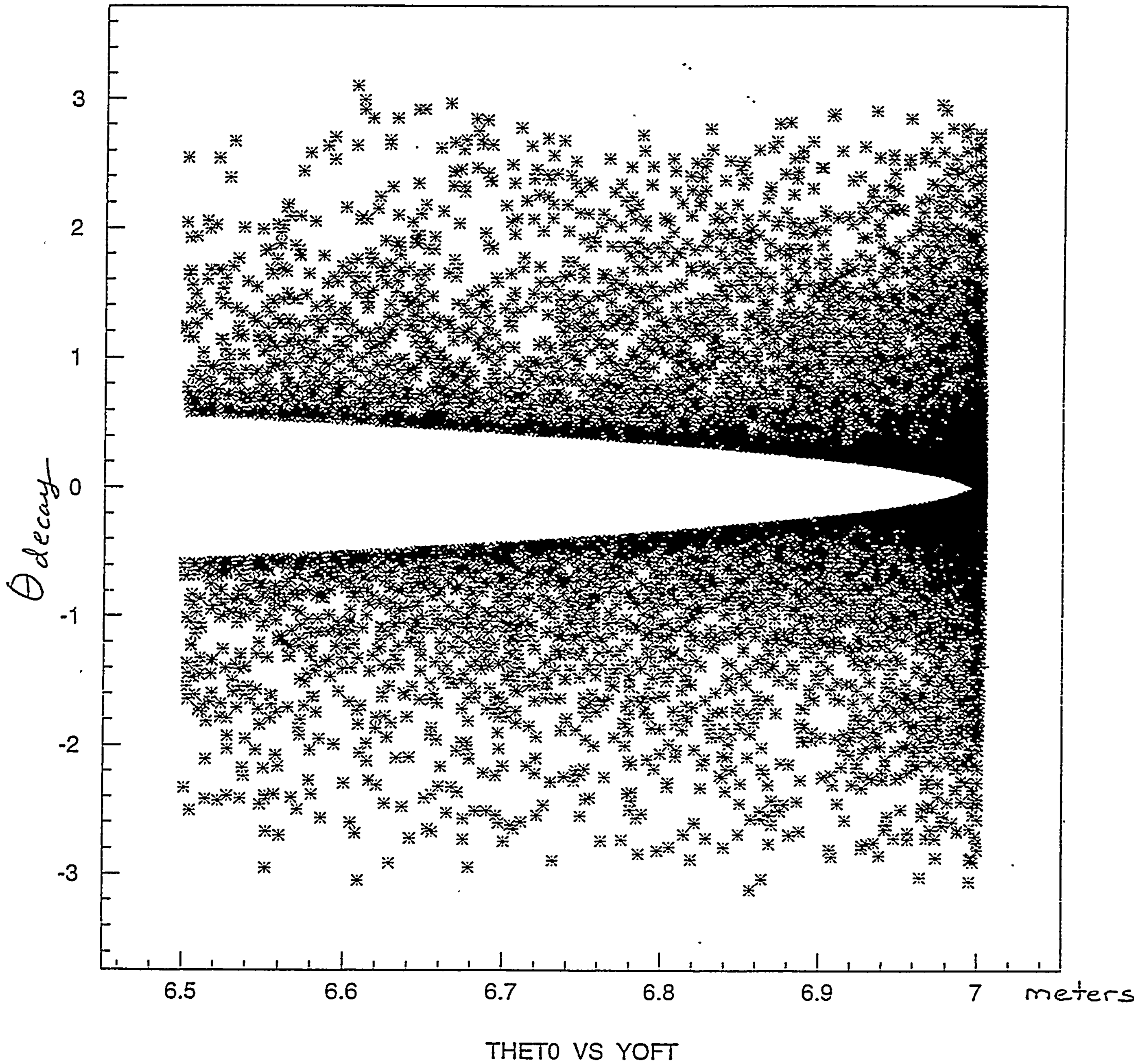


Fig. 1 Radial position (meters) of decay muons at S2 detector vs. center-of-mass decay angle in radians.

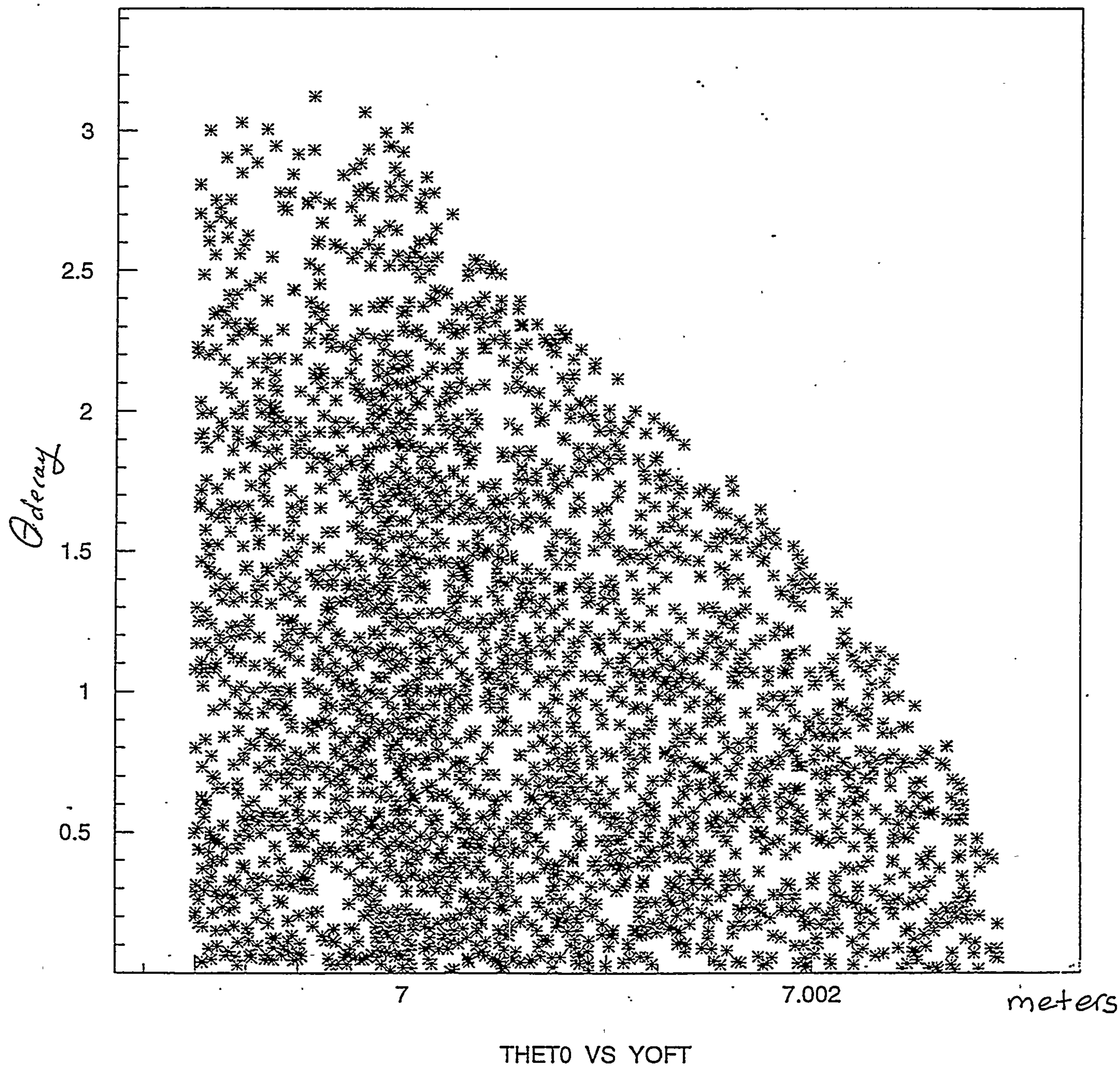


Fig. 2 Expanded section (upper rt) of Fig. 1 showing muon radial position vs. decay angle.

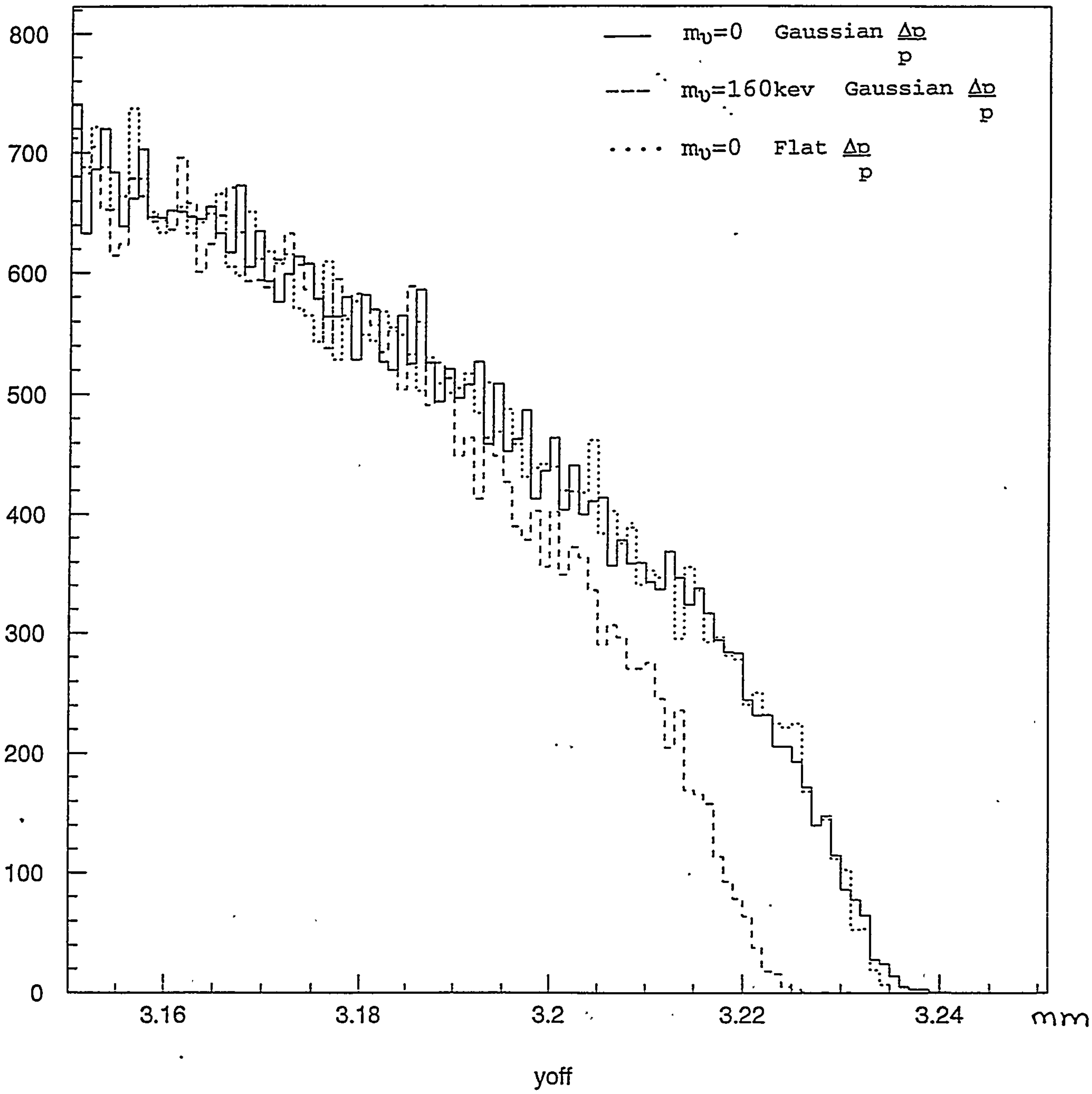


Fig. 3 The position of the muons in mm radially outward from the undecayed pion impact point.

Reasonable, though certainly not optimized, FWHM phase space parameters for the neutrino experiment are 10mm, 0.6mrad (vertical), 10mm, 1.2mrad (horizontal). The dp/p of the E821 pion beam at the end of the inflector magnet is 1.25% FWHM. Since we have reduced the horizontal emittance by a factor of nine, dp/p can also be reduced by this factor. The number of produced pions is reduced by the same factor as $dpd\Omega$; ie. a factor of six hundred. This gives approximately 2×10^5 pions per pulse for 7.5×10^{12} protons per pulse. This proton intensity is only 5% of the AGS capacity in the year 2000. For the $\pi - \mu$ decay we are interested in the final 1 mm of the distribution into which only about 1.7×10^{-4} of the decay muons fall. Since approximately 1/10 of the pions decay in a useful region of the first turn, this means that $\sim 10^{-5}$ of the injected pions yield events of interest.

At present, 3 μm resolution has been obtained by using silicon strip detectors of $10\mu m$ pitch and utilizing charge-sharing between the strips or by measuring the drift time (silicon drift chambers)[5]. The very best resolution to date is 1.4 μm [6] for individual particles using 25 μm pitch silicon microstrip detectors (50 μm readout pitch) and serial readout through a 10-bit flash ADC. This resolution is close to the physical limits imposed by fluctuations in the ionization cloud (delta rays, etc.). However, since we are measuring the edge of a distribution, then by recording 10^6 events in the appropriate region, one should be able to measure in principle to order $0.01\mu m$. In practice, other considerations, such as magnet shimming and the pion momentum distribution, will limit the measurement to microns. In order to collect 10^6 events, one would need about 10^{11} injected pions. At the rates mentioned above, this corresponds to about 280 hours. If a collimator is required to limit the momentum spread, then the rate would be less and the running time subsequently longer.

It is very important that different trajectories see the same field. The E821 plan is to shim the field with iron so it is uniform over the 9 cm diameter muon storage region to $\pm 10ppm$ and use current shims to obtain better than $\pm 1ppm$ uniformity. The field will be measured absolutely to $\pm 0.1ppm$. For the neutrino experiment, measuring the field is not sufficient, the uniformity itself must be adequate. To get a feeling for the effect, if one trajectory sees a uniform field, but another trajectory sees a change in field of $1ppm$ from 180° to 360°, this will give a horizontal displacement after one turn of 10^{-6} of the radius, or about $7\mu m$. Since we can trade pion phase space with pion intensity to get a smaller uniform field region than the E821 9cm diameter circle, the magnetic field uniformity criteria should be possible.

Since we need to put a second detector at a point earlier than 360°, we will need to change the ring magnet optics to produce a focus at this point. For a position at 352°, the horizontal tune becomes

$$Q_x = \frac{360}{352} = 1.023$$

This requires a field index of

$$n = \frac{R}{B}\frac{dB}{dr} = 1 - Q_x^2 = -0.045$$

or dB/dr = 60ppm/cm. The particle motion about the equilibrium orbit in the radial direction is given by:

$$x = x_e + x_m sin(Q_x \frac{s}{R} + \phi)$$

$$x' = \frac{dx}{ds} = \frac{x_m Q_x}{R} cos(Q_x \frac{s}{R} + \phi)$$

A change in the tune will produce a change in the radial position of the particle:

$$dx = dQ_x \frac{x_m s}{R} cos(Q_x \frac{s}{R} + \phi)$$

The magnetic field expansion in harmonics is given by:

$$B(r, \theta) = B_0 + B_1 r cos(\theta) + B_2 r^2 cos(2\theta) + ...$$

Therefore

$$dn = 2Q_x dQ_x = \frac{R}{x_m}(\frac{dB_1}{B_0} + ...)$$

where B_1 is evaluated at x_m. Solving for dx at the focus in terms of dB_1 gives:

$$dx = \pi R \frac{dB_1}{B_0}$$

The current shimming system produced for E821 will have a stability better than 0.1ppm, which corresponds to $2\mu m$ at the focus from the above equation. It consists of thirty-six dipole correction coils which maintain the stability of the $1.5T$ central field from measurement and feed-back from three hundred-sixty fixed NMR probes. The higher moments are corrected with pole face windings. These are adjusted based on measurements of the beam tube NMR trolley. The maximum adjustment of the magnetic field multipoles at the edge of the 9cm diameter E821 muon storage region with this system is given below. It appears that all the higher order multipoles can be measured and corrected to the needed precision to provide magnetic focussing.

n	dB (ppm)
1	150
2	25
3	10
4	6

The beam could be tuned using the protons which accompany the pions into the ring. Since they do not decay, we could understand and possibly eliminate any residual tails to the pion distribution without the confusion that untagged muon decays would introduce. Since the protons arrive at the second detector at a different time than the pions, it will be easy to separate the two. In addition, it is possible to put a detector behind S2 to tag the muons and thereby eliminate any pions that might somehow stray into muon endpoint region. Considering how well the magnet can be tuned and the fact that the endpoint is 3 mm away from the pion impact point, it appears that this additional rejection factor may not be necessary.

2.3 Some Thoughts on the Temporal Domain Measurement

In the temporal domain, one can exploit the fact that individual muons can cycle the ring for a thousand turns before decaying to electrons, which converts a part in 10^6 experiment into a part in 10^3. For the forward going muon decays, a reduction in muon momentum due to a massive neutrino will result in a smaller orbital radius, and hence faster circulation. The period of a particle is given by:

$$T = 2\pi m\gamma/(eB) = 2\pi[mc^2\gamma]R/[Pc^2] = 2\pi E(GeV)R(meters)/[cP(GeV/c)]$$

Muons with non-zero decay angles will also have a shorter period, so this method relies on collimating the beam down to several millimeters, such that only the forward decay muons are stored. A 160 keV mass neutrino would produce a forward going muon with a 400 psec difference in the leading edge after 1000 turns. Muons which decay later than one turn will also confuse the time measurement, since the pion period is 33 ps/turn longer than the muons. Therefore, the final collimator (3/4 of the way around the ring) must actually strip off the pions which have not yet decayed. A time distribution produced by the same Monte Carlo discussed above is sharp enough for picosecond timing; this is not the problem.

In this experiment, the pions are kicked into orbit using the g-2 kicker magnet in the storage ring so the particles do not hit the inflector as they circulate. The kicker could actually be used a second time to kick protons (and pions) into the electromagnetic calorimeters around the inside perimeter of the ring in order to tune up the timing. There can be no multiple scattering in this experiment, so the time measurement must be made without disturbing the beam. In the spatial domain, destructive sampling allows one to acquire statistics a particle at a time, but there is no detector which can make a timing measurement one particle at a time.

For example, a possible candidate detector could utilize electrooptic techniques: a birefringent crystal in proximity to a moving charge can detect its electric field by being sensitive to the rotation of the polarization vector thus induced. A laser beam passing through a polarizer, a crystal, and a second polarizer at right angles to the first, will only emerge from the exit polaroid if the axis of polarization is rotated. Therefore, when the particles pass by, a signal in a fast photodiode observing the exit polaroid is induced.[7] Such systems can currently achieve femtosecond resolution when applied to the currents passing along the traces of integrated circuits.[8] They are also proposed for measuring the time structure of particle beams, both non-destructively [9] and destructively [10]. At several stations around the ring, 4-8 crystals would surround the beam. However, scaling the sensitivity of commercially available probes (1 mV/20 μm) to that of a crystal 1 mm from the beam and path length along the crystal (parallel to the beam) of 5 cm, implies we need an electric field of 0.04 V/m, which is orders of magnitude too small to detect individual particles. The sensitivity would have to be improved using signal averaging techniques over many turns of the ring. For example, the laser can be operated as an interferometer, where one arm contains a variable optical delay before being summed with the signal passing through the crystal. Many runs with small differences in the optical delay would build up a profile of the time distribution. TiSapphire lasers have 150 fs pulses every 12 ns, so that every 12th pulse could be in time with the period by proper tuning of B-field and laser cavity. It seems that there are some avenues for further research, but this is a much more difficult and detector-dependent approach.

The highest flux we can obtain in the future with accumulator (x6.5) and lithium lens (x5) is 33×10^8 pions, but we only accept those within a 4 mm aperture, which brings us down to $\sim 1.5 \times 10^5$ pions. Muons which decay sufficiently forward are only 10^{-5} of the pions, leaving us with only several useful events per turn. In addition, the timing of the pions needs to be as good as the muons, since, as in the spatial domain, this is inherently a difference measurement between pions and the muon endpoint. Since the pions will be removed after 3/4 of a turn, they can be measured destructively. Eventually the centroid of the pion time distribution must also be known to tens of ps. This may be possible after collecting 10^6 events, provided the magnet can be kept stable.

Considering the substantial R&D necessary to produce a reasonable proposal in the temporal domain, most of our effort was spent in understanding the spatial domain. It is left to the interested reader and adventurous experimenter to come up with a possible scenario for the temporal domain.

2.4 Conclusions

A precise measurement of the momentum difference $\Delta p = p_\pi - p_\mu$ in the 2-body decay $\pi \rightarrow \mu\nu$ is sensitive to the neutrino mass. By making the measurement on 3 GeV pions in flight, one is no longer limited by uncertainties in the pion mass measurement. The E821 (g-2) muon storage ring provides a precision spectrometer whose parameters are well matched to the rigors of a $\Delta p/p \sim 10^{-7}$ measurement. The outer edge of the radial distribution of the decay muons is compared to the position of the undecayed pions. By making this measurement in only two detectors (position in and position out) at the focii of the re-tuned g-2 magnet, a particle at a time for one turn in the ring, it appears possible to obtain several micron resolution. This corresponds to a neutrino mass sensitivity of 30 keV.

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AGS SEARCH FOR EVIDENCE OF A LOW MASS GLUON-GLUINO BOUND STATE

WORKSHOP PARTICIPANTS :
J.R.Kane, G.R.Farrar, Y.Kuang, A.D.Hancock, R.E.Welsh, E871 Collaboration

INTRODUCTION :

A proposal is made to search at the AGS for the supersymmetry-based R^0 hadron in terms of various decay channels, each involving a photino $\tilde{\gamma}$. As elaborated in the work of Farrar,et al[1-5] there are several attractive supersymmetry -breaking scenarios involving zero-mass gauginos at tree level that take on a small mass in radiative loop corrections. Thus the gluino is in the range of 0.1-to-1.0 GeV and the photino 0.1-to -1.5 GeV. The gluino would express itself in color octet states, bonding to a gluon ($\tilde{g}$ g), another gluino ($\tilde{g}$ $\tilde{g}$), or a q $\bar{q}$ pair ($\tilde{g}$ q $\bar{q}$). The first of these, the spin 1/2 R^0 hadron, is the lightest with a mass range of 1.3-to-2.2 GeV and a long lifetime. An estimate of the lifetime is given by

$$\tau_R > [10^{-10}\text{-to-}10^{-7}] \times [M_{sq}/100]^4 \text{ (sec)}$$

for a squark mass M_{sq} in GeV. The range 10^{-10}-to-10^{-7} corresponds to a range for r of 1.6-to-2.0 where r is the ratio of R^0 mass to photino mass. This r range would allow the photino to serve the role of cold dark matter. Both the mass and lifetime of the R^0 put it within reach of kaon decay experimental configurations at the AGS and FermiLab.

This presentation focuses on a proposed search for evidence of the R^0 which can be conducted in the neutral B5 beamline. The basic process would be p+p goes to a gluino pair ($\tilde{g}$,$\tilde{g}$) + X, with each gluino emerging as a constituent of an R^0 hadron. The E871 detector in its present configuration would be used to look for two-pion vertex events originating in the decay volume. These would be characterized by invariant mass and transverse momentum values which are large relative to that for a reconstructed neutral kaon.

Other search options at the AGS could use beams of negative pions or kaons, as well as antiprotons.. In this case the process of producing R^0s should benefit from the availability of valence antiquarks in the initial state. This charged beam approach, however, will not be developed here. We will also not address the topic of light supersymmetric baryons which are systems consisting of 3 quarks and a light gluino. A search for evidence of this system has recently been made at FermiLab by the E761 collaboration[6].

MOTIVATION

Given that a light gluino below a mass of 1.5 GeV has not been ruled out, members of the AGS E871 collaboration have been exploring the sensitivity of our double spectrometer detector as applied to a search for R^0 decays. Preliminary simulation studies indicate that considerable sensitivity to certain expected decay modes is available using the present experimental configuration. This investigation is described below.

If the production cross section for R^0 hadrons can be determined it will be possible to reliably estimate our experimental reach in restricting certain portions of the R^0 mass and lifetime space. For this reason recent total cross section calculations by Carlson, Dorata, Morgan, and Sher [7] of the probability for gluino production provide a good starting point.

DECAY MODES OF THE R^0 HADRON

Two and three body decay modes primarily contribute, although some of the expected 2-body channels are suppressed by approximate C invariance of SUSY QCD. Thus $R^0 \rightarrow \pi^0 + \tilde{\gamma}$ and $R^0 \rightarrow \eta + \tilde{\gamma}$ are suppressed since the R^0, π^0, and η have C = +1, but the $\tilde{\gamma}$ has C = -1. While the 2-body decays $R^0 \rightarrow \rho + \tilde{\gamma}$ and $R^0 \rightarrow \omega + \tilde{\gamma}$ are not suppressed (C = -1 for ρ and ω), the large mass of the ρ and ω could limit the utility of these channels in searching for the R^0.

Given these limitations for 2-body decay channels, the 3-body channel $R^0 \rightarrow \pi^+ + \pi^- + \tilde{\gamma}$ can be considered the most significant channel for a search. It provides 90% of the 3-body decays, the neutral pion-pair case contributing the remainder. By comparison the four and five body decays involving pions and a photino are greatly reduced by phase space.

EXPERIMENTAL APPROACH

The E871 spectrometer detector is optimized for the acceptance of dilepton pairs from K_L decay.. Here the approach is to normalize dilepton events to $K_L \to \pi^+\pi^-$ events which have a max transverse momentum of p_t = 206 Mev/c. The double spectrometer renders these pion tracks parallel after the second magnet.

When the spectrometer is applied to the process $R^0 \to \pi^+\pi^-\tilde{\gamma}$ for R^0 and photino mass values of 1.7 GeV and 1.1 GeV, respectively the acceptance for the two pions is clearly lower than for the two pions from K_L.decay. As expected pions from R^0 decay have a tendency to outbend following the spectrometer due to the higher p_t involved. We have calculated for this process that 3/4 of the events have a 2-pion invariant mass that is larger than the K_L.mass. This is regarded as a prime signature for the process, which is not expected from the decay region by other mechanisms.

A simulation of this 3-body decay channel has been carried out for the E871 geometry assuming the following:

1. R production rate: $N_0(R^0) \sim 1 \times 10^{-4}\ N_0(K_L)$
   (This rate, based in part on the gluino total cross section work of Ref [7]), is an approximate quantity.)
2. m_R = 1.7 GeV/c^2 ; $m_{\tilde{\gamma}}$ = 1.1 GeV/c^2 (sample values)
3. $c\tau_R$ = 16 m (the R^0 lifetime is taken as similar to the K_L).
4. The R^0 momentum distribution is taken as similar to the K_L.
5. $Br(R^0 \to \pi^+\pi^-\tilde{\gamma}) \sim 6 \times 10^{-3}$ (from phase space alone, i.e., ignoring the suppression of 2-body channels by C-violation)

An estimate of the signal rate for $N(R^0 \to \pi^+\pi^-\tilde{\gamma})$ for 2π invariant mass > 0.550 GeV/c^2 is then given by

$$\frac{N\left(R^0 \to 2\pi\tilde{\gamma}\right)}{N\left(K_L^0 \to 2\pi\right)} = \frac{N_0\left(R^0\right)}{N_0\left(K_L^0\right)}\ \frac{Br\left(R^0 \to 2\pi\tilde{\gamma}\right)}{Br\left(K_L^0 \to 2\pi\right)}\ \frac{A\left(R^0 \to 2\pi\tilde{\gamma}\right)}{A\left(K_L^0 \to 2\pi\right)} = 10^{-6}$$

where $N_0(R^0)/N_0(K_L) \sim 10^{-4}$;
$Br(R^0 \to 2\pi\tilde{\gamma})/Br(K_L \to 2\pi) \sim 6 \times 10^{-3}/2.03 \times 10^{-3}$; and

$A(R^0 \to 2\pi\tilde{\gamma})/A(K_L \to 2\pi) = 8.6 \times 10^{-6}/2.6 \times 10^{-3}$
(This acceptance ratio is generated by the simulation)

Based on the $K_L \to 2\pi$ event rate at 20×10^{12} protons per pulse on target, this would imply that evidence for an R^0-like 2π event could appear in a matter of hours. Brief studies have shown, however, that the high invariant mass region ($m_{2\pi} > 550$ MeV) requires particle identification for pions to control background. The nature and level of this background will ultimately determine the ability of this approach to produce evidence for high 2π invariant mass consistent with the process $R^0 \to \pi^+\pi^-\tilde{\gamma}$. Additional caution is called for since the differential cross section for R^0s (and not the total as used here) is needed but is not yet available. This could be one-to-two orders of magnitude lower than estimated here.

Since this search seems within reach for the E871 spectrometer, we intend to make a more detailed analysis of rates and backgrounds. The differential cross section is being calculated by Carlson, et al and should be available soon. Hopefully this will encourage us to move to the proposal stage in time for the 1997 running period.

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AGS-2000
Workshop on AGS Experiments for the 21st Century
May 13 - 17, 1996

PARTICIPANTS

NAME	AFFILIATION
Abadjev, Vadim	Institute for Nuclear Research, Moscow
Adair, Robert	Yale University
Adams, Gary	Rensselaer Polytechnic Institute
Adler, Stephen	Brookhaven National Laboratory
Appel, Robin	University of Pittsburgh
Bachman, Mark	University of California at Irvine
Badalian, Ruben	Joint Inst. for Nuclear Research, Dubna
Barakat, Basem	Louisiana Tech University
Barnes, P.D.	Los Alamos National Laboratory
Barnes, Ted	Oak Ridge National Laboratory
Bassalleck, Bernd	University of New Mexico
Bekrenev, Vladimir	Petersburg Nuclear Physics Institute
Berdoz, Alain	Carnegie-Mellon University
Blackett, Kathleen	University of Tennessee
Blecher, Marvin	Virginia Tech
Bock, Greg	Fermilab
Briscoe, William	BNL/George Washington Univ.
Bryman, Douglas	TRIUMF
Buchalla, Gerhard	Fermilab
Calen, Hans	Uppsala University
Carroll, Alan	Brookhaven National Laboratory
Cason, Neal	University of Notre Dame
Chiang, I-Hung	Brookhaven National Laboratory
Chrien, Robert	Brookhaven National Laboratory
Chung, S. U.	Brookhaven National Laboratory
Clajus, Martin	University of California, Los Angeles
Comfort, Joseph	Arizona State University
Cotanch, Stephen	North Carolina State University
Crawford, Hank	Lawrence Berkeley National Laboratory
Cummings, John	University of Massachusetts, Dartmouth
Cushman, Priscilla	University of Minnesota
Dalkarov, Oleg	Lebedev Institute, Russian Academy of Sciences
Derbenev, Y. A.	University of Maryland

Diwan, Milind	Brookhaven National Laboratory
Djilkibaev, Rachid	Institute for Nuclear Research, Moscow
Doornbus, Jaap	TRIUMF
Efendiev, Alesker	Joint Inst. for Nuclear Research, Dubna
Eugenio, Paul M.	University of Massachusetts, Dartmouth
Farrar, Glennys	Rutgers University
Frank, James	Brookhaven National Laboratory
Franklin, Gregg B.	Carnegie-Mellon University
Fukuda, Tomokazu	INS, Univ. of Tokyo
Gibson, Benjamin F.	Los Alamos National Laboratory
Glenn, Woody	Brookhaven National Laboratory
Goodwin, David	U.S. Department of Energy
Gordon, Howard	Brookhaven National Laboratory
Greene, Senta	Vanderbilt University
Guryn, Wlodek	Brookhaven National Laboratory
Gutierrez, Gaston	Fermilab
Hackenburg, Robert	Brookhaven National Laboratory
Haggerty, John	Brookhaven National Laboratory
Hancock, A. Dayle	College of William and Mary
Hebert, Michael	Stanford University
Heppelmann, Steven	Pennsylvania State University
Hertzog, David	University of Illinois
Hoff, Gloria	University of Illinois at Chicago
Hoff, Ramon	Harold Washington College
Holstein, Barry	Univ. of Massachusetts, Amherst
Iachello, Francesco	Yale University
Ieiri, Masaharu	KEK
Imai, K.	Kyoto University
Imazato, Jun	KEK
Isenhower, Donald	Abilene Christian University
Ito, Mark	CEBAF
Ito, Takeyasu	University of Tokyo
Iwasaki, M.	Meson Science Lab, Univ. of Tokyo
Kane, John	College of William & Mary
Kettell, Steve	Brookhaven National Laboratory
Kinoshita, Kay	Virginia Tech
Kirk, Thomas	Brookhaven National Laboratory
Kishimoto, Tadafumi	Osaka University
Koetke, Donald D.	Valparaiso University

Konaka, Akira	TRIUMF
Korotkikh, Vladimir	Moscow State University
Kostin, Mikhail	Moscow State University
Kruglov, Sergei P.	Petersburg Nuclear Physics Institute
Kullander, Sven	Uppsala University
Kuno, Yoshitaka	KEK
Kurashige, Hisaya	Kyoto University
Kuriki, Masao	University of Tokyo
Kycia, Thaddeus F.	Brookhaven National Laboratory
Lee, Y. Y.	Brookhaven National Laboratory
Leipuner, Lawrence	Brookhaven National Laboratory
Li, Kelvin	Brookhaven National Laboratory
Lieb, Joseph	George Mason University
Littenberg, Laurence	Brookhaven National Laboratory
Liu, Tiebhi	Princeton University
Ma, Hong	Brookhaven National Laboratory
Macdonald, John	TRIUMF
Manweiler, Robert	Valparaiso University
Makdisi, Yousef	Brookhaven National Laboratory
Marciano, William J.	Brookhaven National Laboratory
May, Morgan	Brookhaven National Laboratory
Millener, John	Brookhaven National Laboratory
Miller, Gerald	University of Washington
Miller, Timothy	Vanderbilt University
Minor, Ellsworth	Pennsylvania State University
Molzon, William	University of California, Irvine
Mori, Y.	INS, University of Tokyo
Morse, Bill	Brookhaven National Laboratory
Motoba, Toshio	Osaka University
Nagae, Tomofumi	INS, University of Tokyo
Navon, Itamar	Tel Aviv University
Nefkens, B.M.	University of California, Los Angeles
Nozar, Mina	Rensselaer Polytechnic Institute
Olchanski, Konstantin	Moscow State University
Ostrovidov, Alexander	Univ. of Massachusetts, Dartmouth
Panebratsev, Yuri	Joint Institute for Nuclear Research, Dubna
Parsa, Zohreh	Brookhaven National Laboratory
Peaslee, D. C.	University of Maryland
Perdrisat, Charles	College of William and Mary
Peterson, R. J.	University of Colorado

Piasetzky, Eliazer	Tel Aviv University
Pile, Philip	Brookhaven National Laboratory
Poutissou, Renee	TRIUMF
Ralston, John	University of Kansas
Ransome, Ronald	Rutgers University
Reid, John	Vanderbilt University
Ritchie, J.L.	University of Texas, Austin
Roberts, B. Lee	Boston University
Rohrich, K.	IKP, Forschungszentrum, Julich, Germany
Roser, Thomas	Brookhaven National Laboratory
Sadler, Michael	Abilene Christian University
Sandweiss, Jack	Yale University
Sedykh, Sergei	University of Illinois
Semertzidis, Yannis K.	Brookhaven National Laboratory
Seth, Kamal	Northwestern University
Shinkawa, Takao	KEK
Shrock, Robert	SUNY, Stony Brook
Smith, Gerald A.	Pennsylvania State University
Soni, Amarjit	Brookhaven National Laboratory
Spinka, Harold	Argonne National Laboratory
Stanislaus, Shirvel	Valparaiso University
Stefanski, Ray	Fermi National Accelerator Laboratory
Strand, Dick	Brookhaven National Laboratory
Strikman, Mark	Pennsylvania State University
Sugimoto, Shojiro	INS, University of Tokyo
Supek, Ivan	Rudjer Boskovic Institute, Zagreb
Szymanski, John	Indiana University Cyclotron Facility
Takeutchi, Fujio	Kyoto Sangyo University
Tamura, Hirokazu	University of Tokyo
Tanaka, M.	Brookhaven National Laboratory
Tang, Liguang	Hampton University
Thomson, Gordon	Rutgers University
Tokarev, Michael	Joint Institute for Nuclear Research, Dubna
Trueman, T. Laurence	Brookhaven National Laboratory
Urner, David	University of Illinois
Van Der Schaaf, Andries	University of Zurich
Welsh, Robert	College of William and Mary
Weygand, Dennis P.	Brookhaven National Laboratory
White, David	Rensselaer Polytechnic Institute

White, Hywel	Los Alamos National Laboratory
Willutzki, Hans J.	Brookhaven National Laboratory
Winn, David	Fairfield University
Yamin, Peter	Brookhaven National Laboratory
Yoshii, M.	KEK
Zeller, Michael	Yale University
Zhalov, Daniel	Pennsylvania State University
Zimmerman, David	University of Minnesota

1. Pat Tuttle
2. John Reid
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5. Laura Zarahatos
6. Kam Seth
7. Elaine Zukowski
8. Laurie Littenberg
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