BNL Future Plans

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Abstract

I discuss the prospects for a fixed target physics program at the AGS in the RHIC era.

1. Introduction

In 1999, after almost 40 years of independent existence, the Brookhaven Alternating Gradient Synchrotron (AGS) is scheduled to be pressed into service as an injector to the Relativistic Heavy Ion Collider (RHIC). Although at first sight this seems like the end of an era, in actuality, it represents a very attractive new opportunity. For the AGS is actually needed by RHIC for only a few hours per day. The balance of the time it is available for extracted proton beam work at a very small incremental cost. This represents the reverse of the current situation in which the nuclear physics program gets access to the AGS (for fixed target heavy ion experiments) at incremental cost, while the base cost of maintaining the accelerator is borne by the high energy physics program.

Retaining the AGS for particle physics work would broaden the US HEP program considerably, allowing continued exploitation of the world’s most intense source of medium energy protons. As will be discussed below, there are some very compelling experiments that can best be done at the AGS. These include a determination of the Cabibbo-Kobayashi-Maskawa (CKM) matrix element $V_{td}$, probes of Standard Model (SM) and non-SM CP violation, and low energy manifestations of supersymmetry (SUSY).

2. AGS Upgrades

Table 1. Recent performance of the AGS

|                  | 1994  | 1995  | 1996  | 1997  |
|------------------|-------|-------|-------|-------|
| **Proton Beams:**|       |       |       |       |
| Beam Energy      | 24 GeV| 24 GeV| 24 GeV| 24 GeV|
| Peak Beam Intensity (ppp) | $40 \times 10^{12}$ | $63 \times 10^{12}$ | $62 \times 10^{12}$ | $62 \times 10^{12}$ |
| Typical Beam Intensity (ppp) | $35 \times 10^{12}$ | $55 \times 10^{12}$ | $60 \times 10^{12}$ | $55 \times 10^{12}$ |
| Spill Length     | 1.0 sec | 1.6 sec | 1.6 sec | 1.6 sec |
| Cycle Length     | 3.8 sec | 3.6 sec | 3.6 sec | 3.6 sec |
| Duty Factor      | 26%   | 44%   | 44%   | 44%   |
| Spill Structure Modulation | 50% | 20% | < 20% | 20% |
| Average Beam Current | $1.7 \mu A$ | $2.8 \mu A$ | $2.7 \mu A$ | $2.8 \mu A$ |
| Av. Availability/Best Week | ~ 83% | 82%/93% | 76%/92% | 72%/79% |

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Table 1 shows the recent performance of the AGS for slow extracted proton beam running. It is obvious that the intensity of the AGS has plateaued at about \(6 \times 10^{13}\) protons per pulse. Although this is a formidable intensity, experiments have recently been discussed that could benefit from even more. In the last few years the work of T. Roser and others has indicated that a further step can be made rather economically, using a novel injection scheme that requires very little in the way of additional capital investment. It is based on the use of a broad-band RF cavity (“barrier bucket cavity”) to manipulate the beam stored in the AGS.

![Time Domain Stacking with Barrier Bucket Cavity](image)

Fig. 1. Time domain stacking with two barriers.

The AGS Booster accelerates 2 bunches 7.5 times a second, injecting the bunches into the AGS where they are stacked in boxcar fashion. In the present injection scheme, the AGS accumulates four successive Booster cycles (eight bunches) before accelerating. During the accumulation process, space charge effects begin to deplete the stacked beam (the first bunches dwell 400 msec before acceleration begins), and limit the total amount of beam that can be stored. Since it takes roughly 1 second to accelerate the beam in the AGS and ramp the magnets back down, for fast extracted beam (FEB), the total cycle is about \(1+3/7.5 = 1.4\) sec. For slow extracted beam (SEB), the cycle time is \(\sim S + 1.4\), where \(S\) is the length of the flattop. Recently this has been 1.8 seconds with 1.6 seconds of useful spill; with a few hundred ms of overheads, the SEB cycle time is \(\sim 3.6\) seconds. At present, the Booster can supply \(\sim 1.5 \times 10^{13}\) protons/cycle to the AGS, for a total of \(6 \times 10^{13}\). This works out to 2.7 \(\mu\)amp for SEB.

In the proposed scheme, illustrated in Fig. 1, the beam accumulated in the AGS...
is debunched. After the first Booster injection is debunched, an empty RF bucket is imposed on the beam, creating a “hole” in the phase space. A second empty bucket is superimposed on the first, then slowly displaced, broadening the hole in the beam. A second Booster-load is then injected into this hole. The two RF buckets are slowly moved towards one another until the phase space density of the newly injected protons is equal to that of the rest, after which one RF bucket is turned off. The process is repeated for each successive Booster injection. Since the beam is debunched, about twice as many protons can be accommodated under the space charge limit, i.e. 8 Booster-loads, or 120 trillion protons (TP). However, since an extra 4/7.5 seconds is required to accelerate the additional Booster-loads, one doesn’t quite get twice the average current, and the duty factor is reduced (see Table 2).

Table 2. Possible AGS Intensity Upgrades

|                     | AGS only       | AGS+Accum.    |
|---------------------|----------------|---------------|
| **Slow Extracted Beam:** |                |               |
| Duty Cycle (1s spill): | 33%/28%        | 50%           |
| Average Intensity:   |                |               |
| 4 Booster Cycl./AGS Cycle | 20 TP/s, 3.2µA | 30 TP/s, 4.8µA |
| 8 Booster Cycl./AGS Cycle | 34 TP/s, 5.4µA | 60 TP/s, 9.6µA |
| **Fast Extracted Beam:** |                |               |
| Rep. Rate:           | 1.7s/2.2s      | 1.0 s         |
| Average Intensity:   |                |               |
| 4 Booster Cycl./AGS Cycle | 35 TP/s, 5.6µA | 60 TP/s, 9.6µA |
| 8 Booster Cycl./AGS Cycle | 54 TP/s, 8.6µA | 120 TP/s, 19.2µA |

This scheme increases the average intensity of both fast and slow beams by a factor 1.7, at very modest cost. A further improvement can be made by eliminating the AGS accumulation time which will have grown to > 1 sec, by adding a 1.5 GeV accumulator ring in the AGS tunnel. This is presently envisioned as a ring of 2.5 Kgauss permanent magnets, installed above the present ring. Fig. 2 shows the accumulation cycle for both fast and slow extracted beam. There would then be no contribution at all to the AGS cycle time from the accumulation process. For slow extracted beam, this would yield a factor of up to 3 in average intensity with respect to current performance, and improvement of the duty cycle to 50%. For fast extracted beam, the improvement would be even greater, resulting in an intensity 20% of that of the proposed TRIUMF kaon factory. It is possible that the performance of the AGS could be increased even more than this, since the Booster intensity already exceeds its original specification (∼ 20 TP vs 15 TP). Also, particularly for slow extracted beam, it might be possible to accumulate more than eight Booster-loads.

Table 2 gives the expected performance of the AGS without and with accumulator, assuming four or eight Booster-loads of 15 TP each.

To summarize, for SEB running with the barrier bucket scheme only, one can expect to reach 34 TP/sec, with a 28% duty factor (or, for example, 29 TP/sec with a 39% duty factor). Adding an accumulator ring, one can reach 60 TP/sec with 50% duty factor. This is to be compared with recent running conditions of 17 TP/sec with 44% duty factor.
3. The physics program

The possible program for the AGS after 1999 was extensively discussed at the AGS-2000 Workshop [3]. The object was to select a set of compelling experiments that either were unique to the AGS, or were clearly best done there. A number of promising possibilities were identified. Since the workshop, there has been a further filtering of these possibilities. Because almost all the most interesting candidate experiments for this era will be covered by separate talks at this workshop, I will be relatively brief in my discussion of them.

3.1. E940 (MECO)

Muon conversion in the field of a nucleus is a classic probe of lepton flavor violation. In this reaction, a stopped $\mu^-$ is converted into an electron of energy $\approx m_\mu c^2$. Since the nucleus can remain in the ground state, coherence is possible, which tends to make this more sensitive than other tests of lepton flavor conservation such as $\mu \rightarrow e\gamma$. A typical example is given in Table 3 which shows the reach of various types of measurement for an interaction mediated by a generic horizontal gauge boson [4]. One should note not only how well $\mu - e$ conversion stacks up against the competition, but also how large the mass reach is in absolute terms, when one considers that the present upper limit [5] is $7.8 \times 10^{-13}$.

The hierarchy of Table 3 is model dependent, but $\mu - e$ conversion generally comes out very well in this kind of comparison, unless explicitly suppressed. The coincidence of
Table 3. Relative sensitivity of various lepton-flavor-violating processes.

| process                      | $M_H$ reach of a $10^{-12}$ experiment |
|------------------------------|----------------------------------------|
| $\mu^- N \rightarrow e^- N$ | 300 TeV                                |
| $\mu \rightarrow 3e$        | 40 TeV                                 |
| $\mu \rightarrow e\gamma$  | 85 TeV                                 |
| $K_L \rightarrow \mu e$     | 230 TeV                                |
| $K^+ \rightarrow \pi^+ \mu^+ e^-$ | 150 TeV                              |

two factors has greatly stimulated interest in this process. Recent work on flavor violation in supersymmetric GUTs indicates $\mu - e$ conversion at levels two or three orders of magnitude below the current upper limit would be very natural. This is illustrated in Fig. 3. Secondly, proponents of muon colliders have emphasized the very large production of low energy pions (and therefore muons) by medium energy proton beams striking heavy targets. Since the signature for $\mu - e$ conversion, the appearance of an electron of energy $\approx m_\mu c^2$ out of a stopped muon beam, does not require a coincidence experiment, an extremely interesting opportunity arises.

![Fig. 3. Prediction of Ref. 7 for $\mu - e$ conversion for various values of the supersymmetric parameters compared with current upper limit and with projected single event sensitivity of AGS-940.](image)

Bill Molzon and his collaborators have seized the moment to propose a new experiment [8], based to a large extent on the MELC proposal [9] at the Moscow Meson Factory. Fig. 4 is a schematic of their proposed detector. It is composed of three large solenoidal field regions. A proton beam of $4 \times 10^{13}$/pulse enters the production solenoid from the right and impinges on a heavy production target. The time structure of the beam is a pulse of a few nanoseconds every microsecond. This is done so that one can “wait out” $\pi^-$’s that might otherwise make background through radiative pion capture. One can gate off the detector for the first few hundred ns until all pions decay. To accomplish this, there must be fewer than 1 in $10^9$ “breakthrough” protons between pulses, a very difficult task for
the AGS. Most probably the pulsed structure have to be supplemented with some other technique, such as a pulsed kicker. The large number of low energy pions created in the pulse are efficiently collected by the graded solenoidal field in the production solenoid. Of course the pions are decaying constantly to muons so that during the collection process one has an ensemble of pions and muons, that eventually becomes all muons. Muons are transported and separated by sign by the transport solenoid, and negative muons delivered to the detector solenoid. The aim is to capture on the order of 1 negative muon per 100 incident protons. The muons are captured on a series of thin Al stopping targets. Once again a graded solenoidal field is used to collect the resulting electrons with maximum efficiency. The detector is designed to be blind to electrons from ordinary muon decay which are confined by the field to radii inside the region of detectors. A straw chamber or scintillating fiber tracking array followed by an electron trigger calorimeter are proposed.

Other possible backgrounds are radiative muon capture, muon decay in flight, scattered beam electrons, and cosmic rays. Recently it was pointed out that antiprotons could possibly constitute a significant source of background.

3.2. $K^+ \rightarrow \pi^+ \nu \bar{\nu}$

This decay mode is extremely interesting because it first arises at the one electroweak loop level in the Standard Model. As a consequence it is suppressed by some nine orders of magnitude with respect to the kinematically identical $K\pi 3$ decay. This makes for a very sensitive probe for new phenomena, of which many have been proposed [10]. In the SM, the branching ratio is given by
where $X(x_t)$ is a kinematic function of the top quark mass, and $X_{NL}^\ell$ is a QCD-corrected kinematic function of the charm quark mass. The hadronic matrix element, so problematical in other weak decays, is determined to $O(1\%)$ from the well-measured $K\ell e\ell$ decay rate [1]. In the current experimental and theoretical situation, the most interesting potential is that of determining $|V_{td}|$ from a measurement of this branching ratio. After next-to-leading-logarithmic order QCD corrections, the intrinsic theoretical uncertainty in $|V_{td}|$, given $B(K^+ \to \pi^+\nu\bar{\nu})$, is $<5\%$ [12], driven mainly by uncertainty in the charm contribution. Of course since $|V_{td}|$ and other input parameters are not yet tied down, the present prediction of the branching ratio is much more uncertain. Imposing constraints from $B - B$ mixing and from assuming the SM origin of CP-violation in the $K$ system, the current estimate of this branching ratio is $(0.6 - 1.5) \times 10^{-10}$ [13].

As everyone here knows, AGS-787 has announced the observation of a strong candidate for $K^+ \to \pi^+\nu\bar{\nu}$ [13] (see Fig 3). That this milestone could be reached with very low background, opens the door to exploiting kaon flavor changing neutral current reactions to make precise measurements of CKM quantities. Of course, we still aren’t 100% certain that the Standard Model applies! The near-term task of AGS-787 is establish whether in fact it does. The branching ratio implied by the observed event, $(4.2^{+9.7}_{-3.5}) \times 10^{-10}$, is consistent within statistics with the Standard Model (SM) estimate, although it is $3 - 4$ times higher. If the central SM prediction is correct, then, as I-Hung Chiang [13] will discuss later in this workshop, E787 is unlikely to get more than a handful of events by the end of 1999. Since $K^+ \to \pi^+\nu\bar{\nu}$ offers probably the theoretically cleanest method of determining $|V_{td}|$, it would be a shame not be able to exploit it fully. Roughly speaking, the relative error on $|V_{td}|$ is about $2/3$ that on $B(K^+ \to \pi^+\nu\bar{\nu})$. Thus, a signal of 5 events would determine $|V_{td}|$ to about $\pm 30\%$. If one could get an additional factor 5 in statistics via an AGS upgrade, this would go to $<15\%$, which would be sensational! Since John Macdonald [14] will discuss the future plans of this collaboration to pursue $K^+ \to \pi^+\nu\bar{\nu}$ in the AGS-2000 era, I will be relatively brief.

Fig. 3 shows the E787 detector. Major upgrades are not thought to be necessary in order to make substantial further progress in the study of $K^+ \to \pi^+\nu\bar{\nu}$.

The plan for future running includes lengthening the present AGS spill so that the experiment can accumulate more sensitivity per hour without increasing its instantaneous rate capability. If a total of 60 $TP$ could be devoted to E787, a factor $\sim 1.7$ increase would be possible. This is what allows the experiment to project a single event sensitivity in the $2 - 4 \times 10^{-11}$ range in the near term. Simply turning up the wick by another factor five would not be easy. Trigger and random veto dead-times, not to speak of off-line background, would become very hard to fight at that level. Instead, to exploit an increase of available protons one might consider reducing the incident $K^+$ beam momentum from 700 $MeV/c$ to perhaps 550 $MeV/c$. This would allow a substantially greater yield of stopping $K^+$ per incident $K^+$. Right now this ratio is only about $1/2$. It might be possible to make it as high as $1/25$. In this case, for about twice the number of protons on the production target one would have the same number of $K^+$ incident on the degrader, but
Fig. 5. E787 candidate for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$.

$\sim 1.6$ times as many would be stopped. We are confident of being able to sustain this rate since we have found through several changes of the beam momentum that instantaneous rates in the detector are roughly proportional to the rate of $K^+$ which interact in the degrader. If the available proton flux were not sufficient to do this and to lengthen the spill, a shorter, $(14.7 \text{ m vs the present } 19.4 \text{ m})$, higher-acceptance beamline could be built, which would provide a factor two in $K^+$ per proton. Another measure would be to exploit the phase space for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ with $p_\pi < 205 \text{ MeV/c}$. Presently, we use only the $20\%$ of phase space with $p_\pi > 205 \text{ MeV/c}$, since there are no common $K^+$ decay modes that produce $\pi^+$ with momenta above this value. The E787 detector already samples quite a large region below $205 \text{ MeV/c}$. Potentially, the acceptance of the experiment could be more than doubled. The main barrier is $K^+ \rightarrow \pi^+ \pi^0$ ("$K\pi 2$") decays in which the $\pi^+$ loses energy undetectably in the stopping target, while the $\pi^0$ eludes the photon veto. The stopping target instrumentation has been much improved in recent years and we are hoping (but not promising!) to be able to use this region in our current data. For the future, a scheduled upgrade to the photon veto should help clean up this region, and other expedients are being discussed. The final factor would come in running time. RHIC is scheduled to run 37 weeks/year. If we could use the AGS for 35 of these weeks, we could double the effective running time of our best year so far.

Thus a path is open to improve the precision on $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ to $< \pm 20\%$, and that on $|V_{td}|$ to $< 15\%$, without major upgrades to E787, as long as enough protons could be made available.

3.3. $K_L \rightarrow \pi^0 \nu \bar{\nu}$

The branching ratio for $K_L \rightarrow \pi^0 \nu \bar{\nu}$ is given by Eq. 1 with the moduli of the CKM terms replaced by their imaginary parts. This essentially removes the charm term, and with it, almost all the residual theoretical uncertainty. The uncertainty in the branching ratio given the input parameters is reduced from $\sim 7\%$ in the charged to $\sim 1\%$ in the neutral case. In terms of the Wolfenstein representation $[17]$, $V_{td} = \lambda^3 A(1 - \rho - i\eta)$, where
\( \eta \) characterizes CP violation in weak decays. \( B(K^+ \rightarrow \pi^+\nu\bar{\nu}) \) is sensitive to both \( \rho \) and \( \eta \), while \( B(K_L \rightarrow \pi^0\nu\bar{\nu}) \) is sensitive only to \( \eta \). The contribution of indirect CP-violation to \( K_L \rightarrow \pi^0\nu\bar{\nu} \) is tiny [18] as are the long-distance contributions [19], so that a measurement of the neutral branching ratio will yield an accurate determination of \( \eta \), given 3-generation unitarity and knowledge of \( |V_{cb}| \) (since the rate is actually proportional to \( |Im(V_{ts}^*V_{td})|^2 \)). The current estimate is \( B(K_L \rightarrow \pi^0\nu\bar{\nu}) = (3 \pm 2) \times 10^{-11} \), where once again the extent of the range is given by uncertainties in the input parameters.

If one can add to this a measurement of \( B(K^+ \rightarrow \pi^+\nu\bar{\nu}) \), which as discussed above, is dominated by a term proportional to \( |V_{ts}^*V_{td}|^2 \), one can determine the unitary angle \( \beta \), independent of measurements in the \( B \) system [20,21]. Taking a ratio of the neutral to charged branching ratio removes any uncertainty due to \( V_{ts} \). Figure 6 illustrates the relationship between the unitarity triangle and the two kaon FCNC rates.

An experiment to measure \( B(K_L \rightarrow \pi^0\nu\bar{\nu}) \) that exploits the strengths of the AGS was approved in 1996 [22]. A schematic of the proposed detector is shown in Fig. 8. Using \( 0.5 \times 10^{14} \) protons per AGS acceleration cycle, it is estimated that in 80 weeks of running time, about 70 \( K^0 \rightarrow \pi^0\nu\bar{\nu} \) events could be collected with a background of \( \approx 10\% \). This would yield a precision on \( \eta \) of \( < 10\% \) (if CKM \( A \) were perfectly known). The techniques proposed are as follows. (1) The neutral beam will be extracted at an extremely large angle (\( \sim 45^\circ \)) to soften both the neutron and kaon momentum spectra. This minimizes the flux of neutrons capable of producing background by interacting with vacuum windows or residual gas. To further suppress background from the latter, a vacuum of \( 10^{-7} \) Torr must be maintained throughout the beam region. (2) The beam will be highly asymmetric (4 \( mr \times 125 \text{ } mr \)) to facilitate shielding and afford an extra kinematic constraint. (3) The

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**Fig. 6.** Schematic of AGS-787 detector.
AGS proton beam will be bunched on extraction with rms ≤ 200 \( ps \) every \( \sim 40 \ ns \). The narrow bunch width allows the use of flight time measurement to determine the neutral kaon momentum to a few percent. The soft kaon spectrum (\( \bar{p} \sim 750 \ MeV/c \)) is crucial in allowing this technique to work in a short (10 m) beamline. In addition to the momentum determination, due to the microbunching the massless and other fast debris from the target interaction will arrive at the detector before the kaons of interest, and so can be distinguished from the latters’ decay products. (4) Active shower pre-converters will measure the direction of \( \pi^0 \) photons emanating from the \( K_L \rightarrow \pi^0 \nu \bar{\nu} \) decay. (5) In conjunction with a high resolution scintillating fiber calorimeter based on the KLOE design \[23\], this allows one to fully reconstruct the \( \pi^0 \), independent of any assumptions about the beam. Combining the \( \pi^0 \) with the beam timing information, one can transform into the \( K_L \) center of mass. (6) Hermetic photon vetoing is required. A very conservative extrapolation from photon vetoing performance measured in E787 indicates that an average rejection of \( 10^4 : 1 \) per \( \gamma \) can be achieved. The largest expected background to \( K_L \rightarrow \pi^0 \nu \bar{\nu} \) is the 300-million times more frequent \( K_L \rightarrow \pi^0 \pi^0 \) decay \( (K_{\pi2}) \) when two of the four final state photons are missed. When the two missed photons come from the decay of the same \( \pi^0 \) (“even” case), the two detected photons will reconstruct properly to a \( \pi^0 \). The energy of this reconstructed \( \pi^0 \), in the center of mass system of the \( K_L \), will equal 249 \( MeV/c \) (modulo the resolution). When the two detected photons come from different \( \pi^0 \)’s (“odd” case), they will not generally have an effective mass \( \approx m_\pi \). It’s also an important advantage of low energy kinematics that unvetoed \( K_{\pi2} \) events tend to have rather small values of missing energy and missing mass compared to signal events. As a result, \( K_{\pi2} \) background can be suppressed to \( \leq 10\% \) of the signal.

Other possible backgrounds are \( K_L \rightarrow \gamma \gamma \), \( K_L \rightarrow \pi^- e^+ \nu \), with both charged daughters interacting, \( \Lambda \rightarrow \pi^0 n \), and accidental \( \pi^0 \)’s. These backgrounds have been calculated to be much smaller than that from \( K\pi2 \).
Later in this workshop, Yury Kudenko will talk on recent progress on E926 \cite{22} including the results of beam and prototype tests.

3.4. \textit{T}-violating \(\mu^+\) polarization in \(K^+\mu_3\) decay

In his talk on KEK-246 at this workshop, Masa Aoki \cite{24} discussed the motivation for searching for a \(T\)-violating polarization in \(K^+ \rightarrow \pi^0\mu^+\nu\). Briefly, the need for CP-violation in addition to that given by the SM in order to explain the observed baryon asymmetry of the universe \cite{25} motivates investigating low-energy ‘windows’ where such effects are cleanly identifiable. The CKM matrix gives virtually no \(T\)-violating polarization in \(K^+ \rightarrow \pi^0\mu^+\nu\), opening such a window. Moreover a number of popular attempts to go beyond the Standard Model predict a finite polarization at a level that is experimentally accessible \cite{26}.

If \(T\) invariance is not violated, the \(f_+(q^2)\) and \(f_-(q^2)\) form factors which multiply the \((p_K + p_\pi)\) and \((p_K - p_\pi)\) terms in the \(K\mu 3\) amplitude are relatively real. Therefore \(T\) violation is characterized by the size of the imaginary part of their ratio \(\text{Im}\xi \equiv \text{Im}(f_-/f_+)\). This quantity is in turn approximately proportional to the component of polarization transverse to the \(K\mu 3\) decay plane, \(\varphi_T = (0.2 - 0.3) \text{ Im}\xi\) depending on the phase space sampled.

KEK-246 is very familiar to this audience. Fig 8 is a schematic of the detector. A 660 \(MeV/c\) separated \(K^+\) beam is slowed in a degrader and stops in a highly segmented scintillating fiber target. The trigger is designed to accept \(K^+ \rightarrow \mu^+\pi^0\nu\) decays at rest. Photons from the \(\pi^0\) are detected in a 768-element CsI(Tl) counter array. The muons are tracked and momentum analyzed in a spectrometer built around a superconducting toroidal magnet with 12-fold symmetry. The muons are slowed in wedge-shaped Cu degraders and stop in sets of Al plates at the exit of each of the magnet’s 12 gaps. Counter arrays surrounding the Al stoppers complete the polarimeters. The polarimeters are used...
to search for tracks which enter (but do not exit) at $K^+$ decay time, followed by delayed tracks exiting transversely. Tracks exiting left and right with respect to the entering muon direction are compared. The fringe field is aligned with the $\varphi_T$ direction, pinning the transverse polarization while precessing the allowed longitudinal polarization. The 12-fold symmetry of the detector cancels or at least reduces many possible systematic errors. Summing the results from the 12 polarimeters, one searches for a difference between clockwise and counterclockwise-going decays. Great care has been taken on alignment and control of magnetic fields.

In addition to the 12-fold symmetry of the muon system, because of the stopping geometry, one also has a forward-backward symmetry for the $\pi^0$ direction that can be exploited to control systematic errors. Unfortunately the limits on running time and available proton flux at KEK make it impossible for this experiment to reach its full potential, although it is expected to reach $\sigma_{\varphi_T} = \pm 0.0013$. Since it is believed that the apparatus is

Fig. 9. Schematic of KEK-246 experiment.
capable of much more, the experimenters have submitted a proposal for transporting the experiment to the AGS [27], where a result some four times more sensitive is possible. At LESB3 they could get $5 \times 10^6 K^+/\text{pulse}$ with a $\pi/K$ ratio of $< 0.3$ which should be compared to $3 \times 10^5 K^+/\text{pulse}$ and $\pi/K \sim 7 : 1$ at KEK. This means that most singles rates in the experiment will be comparable at BNL and at KEK, but there will be $\sim 15$ times more usable $K^+$ decays/pulse. Rates proportional mainly to $K$ decays will of course be much higher than at KEK, so that, for example, the CsI shaping time will have to be reduced, more instrumentation will need to be deployed for the MWPCs, and the trigger will have to be upgraded. All in all, however, the necessary modifications to the apparatus are quite modest. The experimenters aim to collect some $3 \times 10^8 K\mu 3$ events in 3000 hours of running, to achieve a statistical sensitivity of $\pm 0.00035$ on $\varphi_T$.

KEK-246 represents a new technique in the study of $T$-violating $\mu^+$ polarization in $K\mu 3$. It looks promising, but it has not quite proved itself yet. A second approach [28] being advocated is to instead push the technique of the most recent previous experiment of this type [29] (also carried out at the AGS). Fig. 10 shows the layout of the proposed experiment. The biggest single improvement with respect to Ref. [29] is the use of a $2 GeV/c$
separated beam. Other improvements include a much larger acceptance, a more nearly complete reconstruction of the decays, a more finely segmented polarimeter, and the use of graphite, instead of aluminum as the polarimeter muon-absorbing material. A beam of approximately 20 million 2GeV/c K\(^+\)'s/AGS pulse is incident on a decay tank in which about 5 million decay. Photons from the \(\pi^0\) decay are detected in a Pb-scintillator calorimeter and \(\mu^+\)'s penetrate the calorimeter and are tracked into the polarimeter where they stop. These muons eventually decay and their daughter electrons are tracked through at least two segments of the cylindrically symmetric polarimeter. The principle here is similar to that of KEK-246 – once again one is looking for differences in the rates of clockwise-going and counter-clockwise-going muon decays. In this case, there are 96 segments as compared to 12 in KEK-246. To properly align the the decay plane with the detector, \(K^+\) decays where the \(\pi^0\) emerges along the beam and the \(\mu^+\) roughly perpendicular to it in the \(K^+\) center of mass are selected by the trigger. There is no spectrometer magnet, but a 70 G solenoidal field is imposed on the polarimeter to precess the muons. The polarity of this field is reversed every AGS pulse. This technique is very effective in controlling systematic errors. The analyzing power of the polarimeter is calculated to be \(O(30\%)\) which is a large improvement over that of Ref. 29. The expected statistical sensitivity of the experiment is \(\sigma_{\nu_T} = 0.00013\) in about 2000 hours of running. This corresponds to an uncertainty of roughly \(7 \times 10^{-4}\) in \(\text{Im} \xi\). Large efforts have gone into studying and minimizing possible systematic errors.

Table 4 compares KEK-246, AGS-936, and AGS-923.

|                        | KEK-246 | AGS-936 | AGS-923 |
|------------------------|---------|---------|---------|
| \(\sigma_{\nu_T}\)     | 0.0013  | 0.00035 | 0.00013 |
| beam                   | stopping| stopping| 2 GeV/c sep. |
| recons. evts           | yes     | yes     | partial |
| \(\mu^+\) stopper      | Al      | Al      | graphite |
| e-detector             | scintillator | scintillator | Al drift chamber or scint. |
| precess \(\varphi_T\)? | no      | no      | yes     |
| precess both allowed \(\varphi\)? | yes | yes | no |
| fwd/bckwd symmetry?    | statistics | statistics | systematics |
| limited by             | beam \(\frac{\pi}{R} = \frac{7}{4}\) | CsI(Tl) rates | rate sensitive |

Both AGS-923 and AGS-926 will also attempt to measure the T-violating muon polarization in \(K^+ \rightarrow \mu^+ \nu \gamma\).  

3.5. Children of \(g - 2\)

There has been a long-standing project at the AGS to improve the measurement of the muon anomalous magnetic moment \((g-2)\) to 0.35 parts per million \([34]\). This represents an improvement by a factor 20 over that of the previous (CERN) experiment \([31]\). AGS-821, which took its first data in 1997, is built around a 7.11m radius superferric storage ring in the form of a continuous “C” magnet with the open side toward the center of the ring. The central field is 1.45 T, and it is designed to store muons at the “magic” momentum of 3.094 GeV/c. Lead-scintillating fiber calorimeters are situated symmetrically at 24 sites around the inside of the ring to detect decay electrons.
Aside from the primary goal of the experiment, it is intended to test CPT by measuring the difference between the \((g-2)\) of positive and negative muons. It is also intended to improve the current limit on the muon electric dipole moment (EDM) by an order of magnitude. Going beyond this, there have been two serious suggestions for reconfiguring the apparatus to serve new experiments.

### 3.5.1. Direct measurement of \(m_{\nu\mu}\)

There’s interest in using the \((g-2)\) ring as a spectrometer to improve the sensitivity to the mass of the muon neutrino by more than order of magnitude [32]. The precision of the most recent previous searches [33] was limited by the uncertainty in the pion mass to \(m_{\nu\mu}^2 < 0.16\,\text{MeV}\). In an in-flight measurement at \(p_\pi \sim 3\,\text{GeV}/c\), this source of uncertainty becomes negligible.

Such a measurement requires position information on an event-by-event basis, and thus requires some changes to the septa and the AGS tune in order to bring a slow-extracted pion beam to the \((g-2)\) ring. The pions will be injected into the ring, much as was done for the 1997 g-2 run. They are then “kicked” into the proper orbit by degrading their energy in 9 cm of beryllium sandwiched between two microstrip detectors. One has to measure a tiny shift in transverse position of the decay muon after one turn in the ring as it passes its parent pion’s entering point to the detector sandwich. Muons of the maximum momentum will deviate by about 3mm from the pion position if \(m_{\nu\mu} = 0\). This will be the endpoint of the spectrum of muon positions, and the game is to determine this endpoint to extremely good precision (see Fig. 11). If a resolution of 1.4\,\mu m can be attained, one can reach a \(2\,\sigma\) sensitivity of 8 keV for \(m_{\nu\mu}\). This assumes detection of a total of \(2 \times 10^{12}\) pion decays, which is estimated to require about 800 hours of beam time.

\[
\begin{align*}
\text{Fig. 11. Monte Carlo simulation for the proposal to measure the } &\nu_\mu \text{ mass in the } (g-2) \text{ ring.} \\
\text{The end point region of the position distribution of muons at the microstrip detector is shown.} \\
\text{Abscissa is the distance from the parent pion position in mm. Solid line is distribution for the case of } &m_{\nu\mu} = 0, \text{ dashed line for the case of } m_{\nu\mu} = 20 \text{ keV and dotted line for the case of } m_{\nu\mu} = 40 \text{ keV.}
\end{align*}
\]

### 3.5.2. A measurement of the muon EDM to \(10^{-24}\,\text{e cm}\)

There is a letter of intent [34] to measure the muon electric dipole moment with a precision of \(10^{-24}\,\text{e cm}\), which represents a factor \(10^6\) improvement over the current state...
of the art. At this level, the measurement becomes interesting from the point of view of supersymmetry \cite{35} and competitive in constraining power with current limits on the electron and neutron EDMs.

To make a measurement at this level, it is proposed to reduce the \((g - 2)\) ring momentum from the magic value to \(\sim 500 \text{MeV/c}\) at which point it is practical to create a radial electric field large enough to cancel the \((g - 2)\) precession. The EDM precession then operates without competition. As in the case of \((g - 2)\), the muon’s parity-violating decay is used to measure its spin direction. One looks for an asymmetry between upward and downward-going electrons as a function of time. This can be done to some level with the present electron detectors, but to reduce systematic errors associated with the controlling the average vertical position of the muons, detectors will be placed on the top and bottom of the vacuum chamber. These will also be optimized for the lower electron energies. Great efforts must be made to control unwanted components of the electric field. The precision needed on mechanical alignment is rather challenging. Fig. 12 shows the scheme proposed for aligning the electrodes.

![Fig. 12. Scheme of electrode alignment showing: (A) muon storage region; (B) electrodes; (C) conductive glass plates with insulating support webbing; (D) ceramic alignment yokes; (E) glass reference rods; (F) hydrostatic reference surface; (G) vacuum chamber; (H) piezoelectric driver; (I) level; and (J) support beam.](image)

To reach \(10^{-24} \text{e cm}\), the muon current must be increased 500-fold beyond that of the \((g - 2)\) measurement. Therefore the ring will be converted to strong focussing, and the beam and target systems upgraded. A lithium lens is proposed for the latter. Pions of \(900 \text{MeV/c}\) will be collected so decay muons emitted backward in the center of mass have the desired \(500 \text{MeV/c}\) momentum and can be transmitted to the \((g - 2)\) ring. This experiment could use the maximum intensity listed in Table 2. To reach the sensitivity goal, about \(100 \text{TP}/1.25 \text{second cycle}\) is required. The AGS would be run in single bunch single fast extracted mode at \(13.4 \text{GeV/c}\). A total of \(10^{15}\) stored muons would be accumulated.
4. Conclusion

Running the AGS for fixed target physics in the RHIC era is extremely cost-effective because it can be done on the margin. The machine is required only 2-4 hours a day for RHIC and so could theoretically be available for > 140 hours/week for 37 weeks/year. For modest cost, the AGS slow beam intensity could be tripled, allowing several interesting new possibilities to become practical. With only one or two experiments running at once, properties of the AGS such as microstructure, primary energy, and duty cycle can be “customized” in a way not practical in a large, diverse program. This would greatly benefit the proposals discussed above and is a key advantage of AGS-2000.

The menu of experiments proposed for the AGS-2000 era include a measurement of $|V_{td}|$, incisive probes of both Standard Model and non-SM CP-violation, and of a number of low energy manifestations of supersymmetry, including a type of lepton flavor violation predicted by GUT-scale SUSY. These are all compelling experiments, and cannot easily be done elsewhere.

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References

1. T. Roser, private communication.
2. M. Blaskiewicz et al., “High Intensity Proton Operations at Brookhaven”, 1995 Particle Accel. Conf. Dallas, Texas, May 1995, to be published.
3. “AGS-2000 Experiments for the 21st Century”, edited by L. Littenberg and J. Sandweiss, Brookhaven National Laboratory, May 13-17, 1996, Formal Report 52512.
4. R. Cahn and H. Harari, Nucl. Phys. B176 135 (1980).
5. F. Reipenhausen, talk at the Sixth Conference on the Intersections of Particle and Nuclear Physics (1997).
6. R. Barbieri, L. Hall, and A. Strumia, Nucl. Phys B445, 219 (1995); N. Arkana-Hamed, H.-C. Cheng, and L. Hall, Phys. Rev. D53, 413 (1996); R. Barbieri and L. Hall, Nuovo Cimento 110A 1 (1997).
7. J. Hisano, et al., Phys. Lett. B391, 341 (1997); Erratum ibid. B397,357 (1997).
8. W. Molzon, $\mu - e$ conversion at BNL (MECO), this workshop; M. Bachman, et al., “A Search for $\mu^- N \rightarrow e^- N$ with Sensitivity Below $10^{-16}$”, AGS-940 (1997).
9. V.S. Abadjiev, et al., “MELC Experiment to Search for the $\mu^- A \rightarrow e^- A$ Process”, INR preprint 786/92 (1992).
10. Y. Grossman and Y. Nir, Phys. Lett. B398, 163 (1997); G. Couture and H. König, Z. Phys. C69, 499 (1996); I.I. Bigi and F. Gabbiani, Nucl. Phys. B367, 3 (1991); K. Agashe and M. Graesser, Phys. Rev. D 54, 4445 (1996); M. Leurer, Phys. Rev. Lett. 71, 1324 (1993); S. Davidson, D. Bailey, and B. Campbell, Z. Phys. C61, 613 (1994); S. Bertolini and A. Santamaria, Nucl. Phys. B315, 558 (1989); F. Wilczek, Phys. Rev. Lett. 49, 1549 (1982).
11. W.J. Marciano and Z. Parsa, Phys. Rev. D53, 1R (1996).
12. G. Buchalla and A.J. Buras, Nucl. Phys. B412, 106 (1994).
13. A.J. Buras and R. Fleischer, TUM-HEP-275-97, [hep-ph/9704376], Heavy Flavours II, World Scientific, eds. A.J. Buras and M. Linder (1997), to be published.
14. S. Adler, et al., Phys. Rev. Lett. 79, 2204 (1997).
15. I.-H. Chiang, K^+ \to \pi^+\nu\bar{\nu} at BNL (BNL E787), this workshop.
16. J. A. Macdonald, Future stopped K^+ \to \pi^+\nu\bar{\nu} experiment, this workshop.
17. L. Wolfenstein Phys. Rev. Lett. 51, 1945 (1983).
18. L. Littenberg Phys. Rev. D39, 3322 (1989).
19. J. Hagelin and L. Littenberg Prog. Part. Nucl. Phys. 23, 1 (1989).
20. G. Buchalla and A. J. Buras Phys. Lett. B333, 221 (1994).
21. G. Buchalla and A. J. Buras, Phys.Rev.D54,6782 (1996).
22. Y. Kudenko, BNL E926: Measurement of K^0_L \to \pi^0\nu\bar{\nu}, this workshop; I-H. Chiang, et al. “Measurement of K^0_L \to \pi^0\nu\bar{\nu}”, AGS Proposal 926 (1996).
23. A. Antonelli, et al., N.I.M. A354 352 (1995).
24. M. Aoki, T-Violation in Stopped K^+ \to \pi^0\mu^+\nu at KEK, this workshop.
25. L. McErran, M. Shaposnikov, N. Turok, and M. Voloshin, Phys. Lett. B 256, 451 (1991); N. Turok and M. Voloshin, Phys. Lett. B 256, 451 (1991); N. Turok and J. Zadrozny, Nucl. Phys. B 358, 471 (1991); M. Dine, P. Huet, R. Singleton, and L. Susskind, Phys. Lett. B 257, 351 (1991).
26. G. Bélanger and C.Q. Geng, Phys. Rev. D44, 2789 (1991); R. Garisto and G. Kane, Phys. Rev. D44, 2038 (1991); G.-H. Wu and J. N. Ng, Phys.Lett. B392, 93 (1997); M.Fabbrichesi and F. Vissani, Phys. Rev. D55, 5334 (1997).
27. J. Imazato, et al., “Search for T-violation in the K^+ \to \pi^0\mu^+\nu Decay Using Stopped Kaons” (1997).
28. M.V. Diwan, T-Violation in In-flight K^+ \to \pi^0\mu^+\nu at KEK, this workshop; M.V. Diwan, et al., “AGS Proposal 923 - Search for T Violating Muon Polarization in K^+ \to \mu^+\pi^0\nu\mu Decay”, (1996).
29. S.R.Blatt, et al., Phys. Rev.D27, 1056 (1983)
30. B.L. Roberts, et al., “Status of the New Muon (g – 2) Experiment”, to be published in the proceedings of the 1996 International Conference on High Energy Physics, Warsaw, (1996).
31. J. Bailey, et al., Nucl. Phys. B150, 1 (1979).
32. P. Cushman, et al., “A New Measurement of the Muon Neutino Mass”, AGS Expression of Interest, Sept 1996.
33. K. Assamagan, et al., Phys. Lett. B335, 231 (1994); M. Daum, et al., Phys. Lett. B265, 425 (1991).
34. Y. Sermertzidis, et al., “Search for an Electric Dipole Moment of Muon at the 10^{-24} e cm level”, Sept. 1997.
35. W. Bernreuther and M. Suzuki, Rev. Mod. Phys. 63, 313 (1991).