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# Antiproton Physics at BNL *

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D.M. Lazarus

Brookhaven National Laboratory, Upton, NY 11973, U.S.A.

**Abstract**

A review of antiproton physics at the Brookhaven AGS in past decade is given as well as a description of the present high energy physics program. Existing and potential facilities for antiproton physics at the AGS are discussed and are found to provide useful antiproton intensities over the momentum range proposed for SUPERLEAR in a multiple user environment.

## 1. INTRODUCTION

SUPERLEAR and KAON can provide unsurpassed facilities for the extension of the research programs discussed here. At the moment the future existence of both machines is uncertain and it behooves us to again regard the facilities available to us until the promise of SUPERLEAR and KAON is realized. The AGS at Brookhaven makes available antiprotons at momenta from .5 to 15 GeV/c in a number of beams that extend the range of LEAR albeit without the purity, duty factor and beam emittance available at a cooled storage ring. In addition to providing access to states beyond the mass range within the reach of existing antiproton facilities, several experiments can be simultaneously accomodated by virtue of a multiplicity of beams, some of which are highly purified.

## 2. HISTORICAL PERSPECTIVE

Following the demise of narrow baryonia and the beginning of the LEAR project at CERN some ten years ago, and with growing interest in rare kaon decays as a probe of the standard model, the role of low energy antiproton physics in the AGS physics program diminished. Nevertheless, several antiproton experiments were proposed and carried out in the intervening years. Notable among them, were the first measurements of the antineutron-proton annihilation and total cross sections and a search for narrow

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structures from threshold to 1900 MeV [1] which used tagged $\overline{n}$'s produced in the charge exchange reaction as projectiles and a search that set stringent limits on the production and decay of the $\xi(2.2)$ [2] which had been reported in $J/\psi \rightarrow \gamma K K$ by the Mark III Collaboration [3] at SPEAR. Two AGS proposals to search for the $\eta_c$ and $\eta_c'$ were stillborn in the expectation that they would not be competitive with R704 at the ISR in terms of rate and resolution. However, when the ISR program was terminated, interest in charmonium formation spectroscopy at BNL was rekindled and a workshop on $\overline{p}$ physics at the AGS was held in the summer of 1986 [4] which produced a several conceptual designs for new high purity antiproton sources in the 2-10 GeV/c range. Recent results on antiproton-nucleus interactions from E854 were presented at this meeting [5].

## 3. THE AGS PROGRAM

The current AGS physics program is diverse and vigorous. The first generation of rare kaon decay experiments has been completed with new limits that are orders of magnitude lower than previously achieved results and three second generation experiments have been approved and are either under construction or being upgraded. These include studies of the lepton family number violating decays, $K_L^0 \rightarrow \mu e$ [6] and $K^+ \rightarrow \pi^+ \mu^+ e^-$ [7] which have set branching ratio limits of $2.4 \times 10^{-11}$ and $2.1 \times 10^{-10}$ respectively which probe the standard model for evidence of new interactions at the mass scale of tens of TeV. Other decays that proceed via flavor changing neutral currents and are therefore suppressed by the G.I.M. mechanism [8] are $K_L^0 \rightarrow \mu^+\mu^-$ [9] and $K^+ \rightarrow \pi^+ e^+ e^-$ [10] which proceed as higher order processes due to the mass differences between quarks. The previous world samples of a few of these events has been increased to hundreds and thousands allowing detailed comparisons with theory. Limits have been improved by several orders of magnitude for the decays $K_L^0 \rightarrow \pi^0 e^+ e^-$ [11] which is CP violating in first order, $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ [12] and and $K^+ \rightarrow \pi^+ \nu \overline{\nu}$ [13]. The first precision branching ratio measurement for kaon Dalitz decay, $K_L^0 \rightarrow e^+ e^- \gamma$ [14] has been made as well as the first observation and branching ratio measurements for $K_L^0 \rightarrow e^+ e^- \gamma\gamma$ [15] and $K^+ \rightarrow \pi^+ \gamma\gamma$ [16].

In addition, this program has made it possible to carry out sensitive searches for light, weakly interacting particles of which the axion is an good example in $K^+ \rightarrow \pi^+ a^0$ [12,17] and $\pi^0 \rightarrow \gamma a^0$ [18] and to obseve the controversial decay $\pi^0 \rightarrow e^+ e^-$ [19] where the $\pi^0$ is tagged in the decay $K^+ \rightarrow \pi^+ \pi^0$. A likely successor to the search for $K^+ \rightarrow \pi^+ \mu^+ e^-$ is a search for CP vioation as manifestedby an asymmetry in the Dalitz plots for $K^\pm \rightarrow \pi^+ \pi^- \pi^\pm$.

Although the rare kaon decay experiments are the centerpiece of the AGS program, the remainder of the program is varied and vital. One search for the doubly strange dibaryon, H, was recently completed and another is in progress. Exotics spectroscopy with the Multiparticle Spectrometer, MPS, where the claim for evidence of three gluonic resonances with quantum numbers $I^G J^{PC} = 0^+ 2^{++}$ in the OZI forbidden process $\pi^- p \rightarrow \phi\phi n$ originated, continued with a recently completed search for enhanced $\phi\phi$ production in $K^- p \rightarrow \phi\phi n$ where sufficient statistics for a partial wave analysis have been obtained and $\bar{p}p \rightarrow \phi\phi\pi^0$. A new experiment incorporating a large, highly segmented lead glass array and a BgO barrel counter to veto soft gammas is being set up in the MPS to study the $M(1405)J^{PC} = 1^{-+}$ reported by the GAMS group [20], the G(1590)$0^{++}$ [21] which exhibits large branching ratios to $\eta\eta$ and $\eta\eta'$ suggestive of gluonium decays, and to carry out a systematic exploration of meson production in $\pi^- p$ interactions in the $1-3$ GeV region.

A major experiment is under construction to study color transparency in pp elastic scattering in nuclei up to 20 Gev/c. The new apparatus, based on a superconducting solenoid and straw tube chambers, will provide twenty times the acceptance of the groups previous spectrometer with which a very large change in transparency was found in the momentum region between 6 and 12 GeV/c [22]. The second phase of the experiment will be to continue the investigation of large angle exclusive hadronic scattering [23]. Operation with the polarized proton beam would allow further measurements of the polarization parameter, $A_N$, at high $P_T$ [24] and of $A_{NN}$ with a polarized proton target.

Construction of a 3 GeV superconducting storage ring for a new measurement of the anomalous magnetic moment of the muon, g-2, is approaching completion. A sensitivity of 0.35 ppm is anticipated for the new measurement or a factor of twenty improvement over the previous effort [25]. This sensitivity will make possible a determination of the virtual radiative contributions of the $W^{\pm}$ and $Z^0$ which is the electroweak equivalent of the Lamb shift in QED.

A 20 Km baseline $\nu_\mu$ disappearance neutrino oscillation experiment has been proposed recently to extend the exploration of the oscillation space $\Delta m^2$ vs. $sin^2 2\theta$ by two orders of magnitude beyond previous accelerator based experiments with three widely spaced, massive imaging water Cherenkov counters.

Finally, active programs of hypernuclear physics and condensed matter studies continue as well as non-accelerator experiments searching for axions.

## 4. ANTIPROTON FACILITIES

The AGS Complex is shown in Fig. 1 and the $\bar{p}$ fluxes available in various existing beams and two hypothetical r.f beams are displayed in Fig. 2. Currently $2 \times 10^{13}$ protons are slowly extracted over a 1.0-1.5 second spill every 2.5-3.0 seconds and divided among four target stations. This is expected to increase threefold to $6 \times 10^{13}$ per cycle implying a potential of $(0.5 - 0.6) \times 10^{13}$ protons per second per target staion assuming equal sharing. In the 1-2 GeV/c range, the 2 GeV Beam, (TGB) [26] antiproton fluxes up to $10^6$ per second are available with purities in excess of 99%. Similar purities albeit with lower fluxes are available in the LESBIII which covers the $\bar{p}$ momentum range down to .5 MeV/c. Unpurified beams exist which can extend the momentum range to 15 GeV/c with more than $3 \times 10^6 \bar{p}$ per second albeit with purities of 1-2%. A duty factor of 30% to 40% is typical for AGS operation. These are facilities that might be best called conventional and depend on the recently commissioned AGS Booster for their large secondary particle yields.

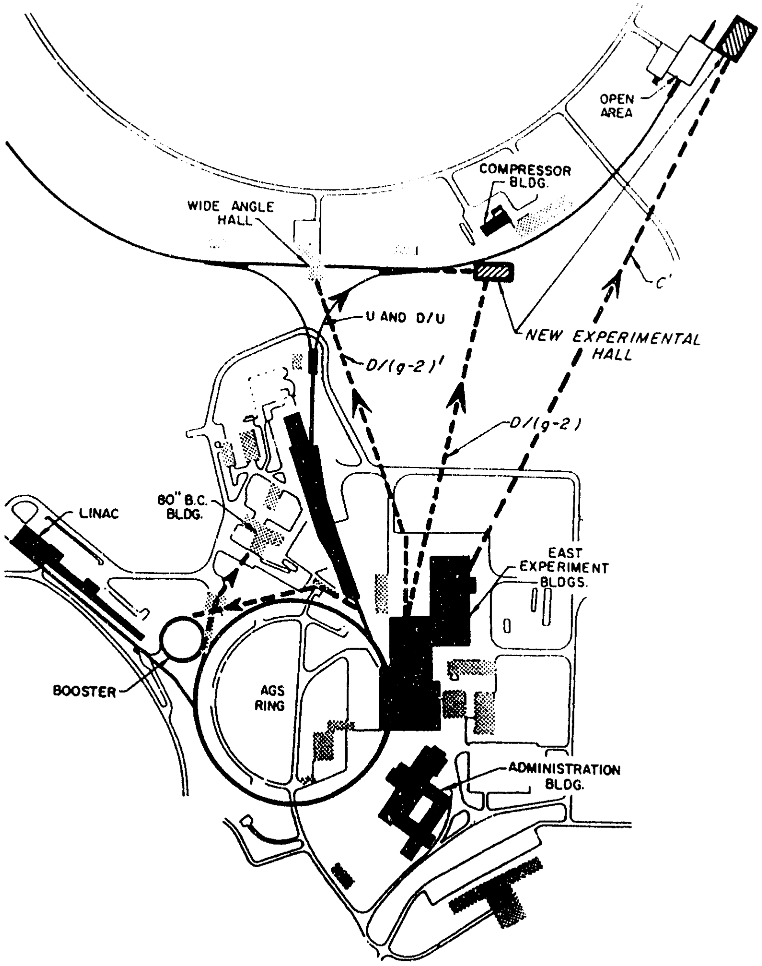

Figure 1. The AGS Complex. The $\bar{p}$ beam options considered in the 1986 Summer Workshop on Antiproton Beams are indicated by the dashed lines. The 1 km decay purified beam line indicated by $C'$ extending from the northeast corner of the East Experimental Buildings to an experimental area indicated by hatching adjacent to the Open Area or 4 O'clock RHIC Hall at the upper right of the figure and the Booster at the lower left are discussed in the text.

The 1986 Workshop identified several possibilities for future high performance, dedicated $\bar{p}$ beams. However, there were essentially three types of purification considered. The first method which is common to all simply employs long beam paths to allow beam pions to decay. The curve for the beam labelled $C'$ in Figure 3 illustrates the degree of purity achievable by this technique. In combination with a high resolution beam spectrometer, a conventional large acceptance 0 degree beam is capable of yielding fluxes in excess of $10^7$ antiprotons per second from 3-10 GeV/c as indicated by $C'$ in Fig. 2. As can be seen from Fig.3, antiprotons constitute only five percent of the flux at 10 GeV/c and thirty percent at 4 GeV/c. Figure 4 displays the momentum

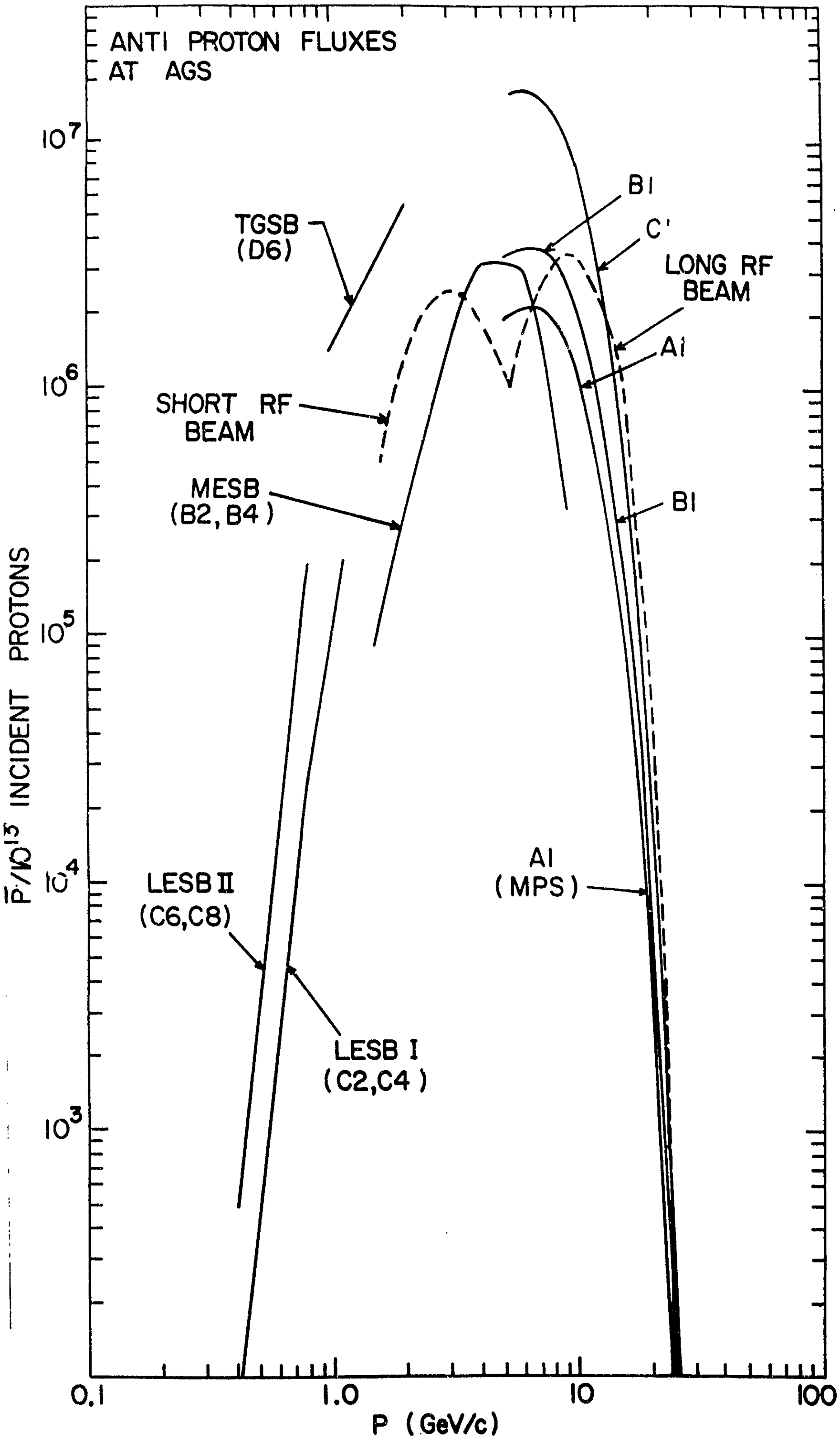

Figure 2. Antiproton fluxes available in existing and potential AGS beams. The fluxes are given per $10^{13}$ protons incident on the production target and $(0.5 - 0.6) \times 10^{13}$ protons per second per target station are anticipated with the AGS Booster.

resolutions and the the center of mass energy resolutions that can be achieved by time of flight in conventional beams of various lengths and with the use of a high resolution beam spectrometer.

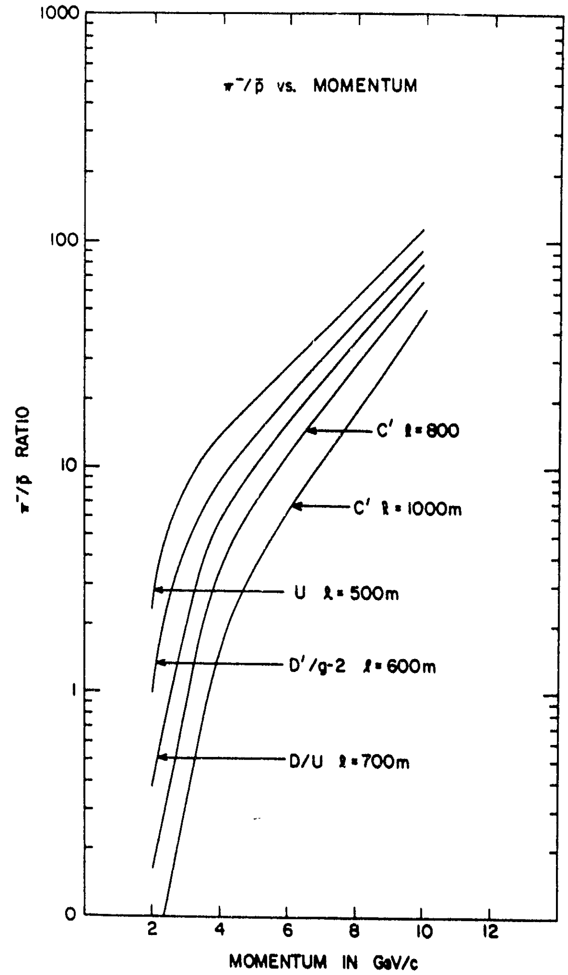

Figure 3. Purity of the $\overline{p}$ beam options using decay over long distances to reduce the pion contamination. The $\pi^-/\overline{p}$ ratio is plotted versus beam momentum. The 1000 meter $C'$ option is discussed in the text.

Some years ago T. Kalogeropoulos [27] proposed the enhancement of long beam purity by the production of secondary particles by protons that are slowly extracted from the accelerator over many revolutions while retaining the bunch structure imposed by the r.f. accelerating field. Momentum analyzed secondary particles are then separated in time according to their relative velocity and flight path. A test was successfully carried out in which protons were targeted in 2.4 ns bursts every 220 ns during spills of several seconds in order to tag antineutron interactions by time of flight and energy deposition. An antiproton beam utilising this technique was designed and described in a technical note [28] that was incorporated in the workshop proceedings.

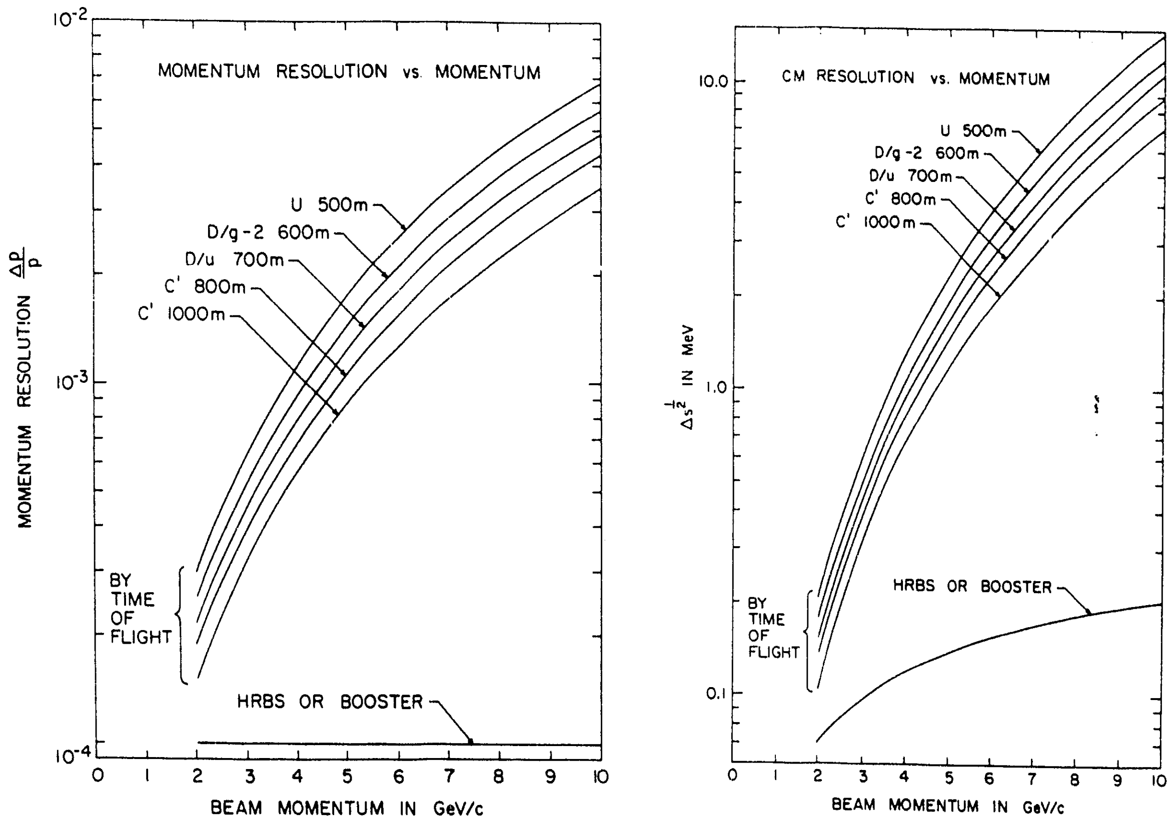

Figure 4. The beam momentum resolution (left) and the center of mass energy resolution, $\Delta s^{1/2}$ (right), as a function of momentum for decay purified $\bar{p}$ beam options as a function of momentum The 1000 meter $C'$ beam is discussed in the text. The momentum definition and $\Delta s^{1/2}$ for these beams with a high resolution beam spectrometer(HRBS) and with the Booster option are also indicated.

The primary problem with this approach is not technical but rather in the loss of compatibility with other experiments which might find the bunch structure unacceptable due to accidentals. A possible solution would be to rebunch the beam at a higher frequency to reduce the average number of triggers per bunch. Since unwanted particles would generally the most numerous, a somewhat whimsical improvement (because of its cost) would be to provide each charged particle beam line with a deflecting mode r.f. cavity tuned and locked to the accelerator r.f frequency with individual phase controls to remove the unwanted particles from the beams of all experiments.

Conventional methods of purifying particle beams include electrostatic and radiofrequency separation. The former is currently used at the AGS for beam momenta below 2 GeV/c. Since the deflection of a particle of charge e, momentum $p_0$ and $\beta = v/c$ in an electric field E of length L is proportional to the to the length of time spent in the field region, the transverse momentum kick $\Delta p_t = eEL/c\beta$ and the angular deflection is $eEL/p_0 c\beta$. Therefore the difference in angular deflection or the separation between particles of the same momentum but different masses is $eEL(1/\beta_1 - 1/\beta_2)/p_0 c \approx eELc\Delta m^2/p_0^3$ for $pc \gg mc^2$ and therefore the method quickly becomes impractical with rising momentum, e.g. for $p_0$ >6 GeV/c for kaon-pion separation and 12 GeV/c for antiproton-pion separation. Since this technique works well in the same range as SUPERLEAR it should be kept in mind that an electrostatically purified beam at the AGS could yield in excess of $10^6$ antiprotons per second in the mass range for exotic meson spectroscopy and charmonium as well as $\Xi$-$\bar{\Xi}$ production. Although complete separation is not likely, recent experience has indicated that an antiproton beam in this energy range can be built with better than ninety percent purity. The relative simplicity and modest cost of electrostatic separation relative to radiofrequency separation make it an attractive alternative for antiprotons at momenta less than 12 GeV/c. It was not considered at the 1986 Workshop since an elecrostatically purified beam, the MESB, which was limited to 9 GeV/c was in operation at that time. However, it was only capable of yielding $10^5\bar{p}$/second with purities of at best 50%, which was typical for beams of what is now considered primitive design in the pre-Booster era. The only virtues of r.f. separation for $\bar{p}$ aficionados would be for accesss to still higher momenta for heavy quark spectroscopy and possibly for the politics of having something built that would serve the kaon enthusiasts as well. It is not necessary to point out that this could be a mixed blessing.

The use of the AGS Booster as an antiproton ring with capability for total purification through decay, acceleration and decelleration, momemtum spread manipulation, and posssibly cooling provides most of the features available at LEAR with an expanded momentum range to a high of 5.2 GeV/c and a low of 20 KeV for devotees of CPT tests with antihydrogen. Fig. 5 illustrates how the Booster might be used as part of an antiproton facility. Fast extraction of three r.f. bunches of protons from the AGS into the 'U' line where they are targetted and the negative particles produced are collected by a lithium lens, transported to and injected into the Booster for acceleration or deacceleration and momentum spread manipulation, and finally transported to an experimental hall while the remainder of the AGS beam is extracted to the other experimental areas. The antiproton beam from the Booster is essentially pure because of the large flight path and large dispersion. Figure 5 shows the 80" Bubble Chamber Building housing the experimental area but this option has been foreclosed by construction of the muon g-2 storage ring which fills the building. However, an addition or an adjacent building could be built which would share the installed amenities such as power and water. The antiproton facility would share the proton extraction system, the' U' Line and target station. The Booster option is compatible with the rest of the program with which there will be the usual competition for protons with other users including those using antiprotons in other beams. Three of the twelve AGS proton bunches to produce antiprotons for the Booster were taken a realistic example. It could, of course, be more or less according to needs and priorities. The $\bar{p}$ momentum resolution and and the center of mass energy resolution, $\Delta s^{1/2}$ are plotted against beam momentum in Fig.4

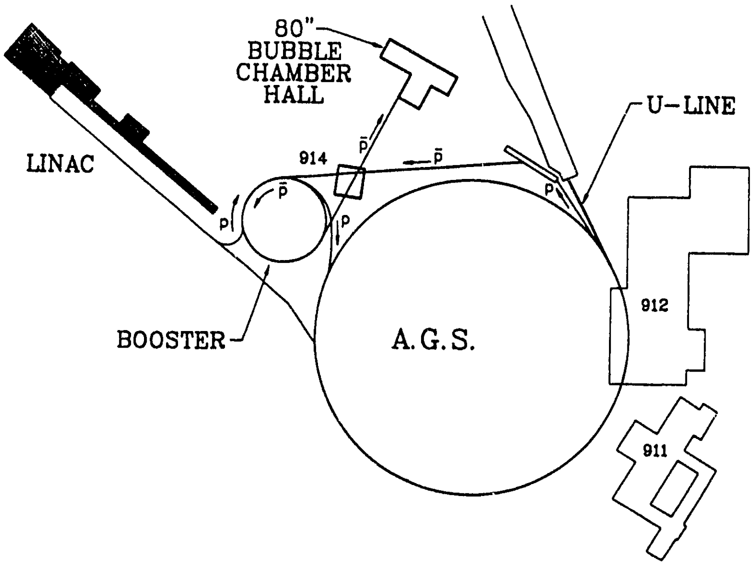

Figure 5. A schematic representation of the Booster option.

Antiproton injection and extraction systems would have to be installed in Booster ring. Injection would take place at 4 GeV/c, the peak of the $\bar{p}$ production spectrum at the AGS. The Booster could then provide $2 \times 10^7$ antiprotons per second between 4 and 5.2 GeV/c with a spill that is free of microstructure and a variable momentum spread which can be made as small as $10^{-4}$ for the study of a resonance that had been found during a sweep with a greater momentum spread, e.g. $\Delta p/p = .02$. The Booster magnets limit the top momentum to 5.2 GeV/c which is barely sufficient to reach the $\chi^0(^3P_0)$ state of charmonium. However, light quark spectroscopy and the search for exotic mesons would have a center of mass energy reach up to 3.4 GeV. Decelleration in the Booster reduces the available betatron phase space as $(p/4GeV/c)^2$ so that the $\bar{p}$ flux at the proton injection momentum of .65 GeV/c (200 MeV kinetic energy) is reduced to $5 \times 10^5$ per second. The kinetic energy dependence of the $\bar{p}$ flux for three AGS proton bunches targetted is displayed in Figure 7.

Ultralow energy antiprotons could made available by further decelleration in the 200 MeV Linac. Approximately $4 \times 10^4$ 200 MeV antiprotons per second could survive to 750 KeV and be further decellerated to 20 KeV in the RFQ. If beam cooling were introduced in order to reduce the $\bar{p}$ beam emittance in the Booster by a factor of twenty, approximately half of the 4 GeV/c $\bar{p}$ flux or $10^7$ per second could survive decelleration

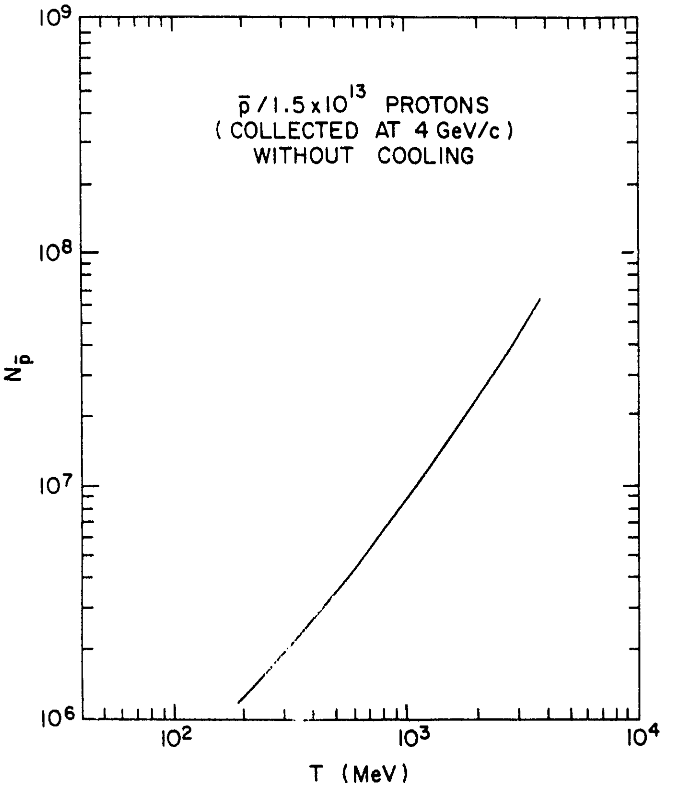

Figure 6. The intensity of decellerated antiprotons in the Booster as a function of their final kinetic energy.

to 20 KeV. There is no reason that antideuterons couldn't be subjected to similar manipulations albeit with very much reduced intensities.

## 5. CONCLUSIONS

At the present time the AGS has purified beams capable of delivering up to $10^6$ antiprotons per second at moment up to 2 GeV/c and unseparated beams that can yield similar fluxes up to 15 GeV/c. Purities of the latter can be enhanced by elecrostatic separation, by beam length and large dispersion or possibly by time separation for essentially the cost of building a long conventional beam. The AGS Booster has the potential for becoming a miniSUPERLEAR for momenta up to 5.2. GeV/c for less than $10^7$ S.F.

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