SEARCH FOR THE "ABNORMAL NUCLEAR STATE" HEAVY, A > 200, ION ACCELERATION IN THE AGS*

K. Prelec and A. van Steenbergen
Brookhaven National Laboratory
Upton, New York 11973

Summary

Recent theoretical work speculates on the existence of abnormal states of matter which could possibly be created as a result of collisions of superenergetic heavy nuclei. For this reason the possibility of acceleration of heavy ions with mass number $A > 200$ to kinetic energies of $1 < T_n < 10$ GeV/nucleon has been studied and found to be feasible without modification of the AGS vacuum and rf systems by using a fast cycling synchrotron as a booster ring. This booster is required in order to obtain the fully stripped ion state, since partially stripped heavy ion acceleration in a slow rise time accelerator is impractical because of extreme vacuum requirements. The fast cycling feature of the booster is essential in reducing transmission losses associated with electron capture or loss during acceleration and beneficial in increasing the final beam intensity.

Introduction

Stimulated by the results of the theoretical work[1,2] of T.D. Lee and G.C. Wick, implying the possible formation of abnormal nuclear states in collisions of very heavy ions, $A > 200$, with single beam primary energies of $T_N > 1$ GeV/nucleon, a study has been made of Hg-U acceleration in the AGS.[3] The results reported here in condensed form indicate the necessity of combining the AGS with a sequence of accelerator components consisting of a 600 kV Cockcroft-Walton preaccelerator for 1 emA of ions, $A > 200$; a $\simeq 0.75$ MeV/amu Sloan-Lawrence linac and a 200 MeV/amu (surplus) fast rise time booster synchrotron. With this system, proton and ion acceleration in the AGS would be readily interchangeable since no modifications would be required for existing AGS subsystems.

In addition to its relevance for the exploration of possible abnormal states of matter, this facility would be unique for[4] studying heavy ion collisions in the domain where hydrodynamic theory predicts the possibility of nuclear densities up to 8 times normal nuclear density as a result of shock wave phenomena; possible formation of elementary particle condensates, such as pions; study of particle production, multiplicities and distributions using very energetic heavy ions; projectile and target fragmentation with relativistic heavy ions; etc.

Limiting Parameters

In order to delineate the maximum energy capability of various accelerators the relationship between particle magnetic rigidity and its kinetic energy for various ε ($\equiv q/A$) ratio's is useful. This is shown in Fig. 1. This also indicates the relevance of the present study, also with regard to the eventual capability of the Bevalac (LRL) accelerator since with a ($B\rho$) value of 23 Tm (Bevatron) a kinetic energy of approximately 2 BeV/nucleon could only be reached when using the fully stripped ion state ($\varepsilon = 0.4$ for Hg, $\varepsilon = 0.38$ for U), which is not achievable with the Bevalac heavy ion injector.

*Work performed under the auspices of the U.S. Energy Research and Development Administration.

Because of the very active ongoing particle physic program using the 30 BeV proton beam from the AGS, the constraint was adopted that no significant change in an of the AGS subsystems would be acceptable, in order to accelerate heavy ions in the AGS. An examination of the simplest accelerator combination, i.e. a van der Graaff-AGS system indicated that with a source: 0.1 emA, U^{8+}, 10 MV single stage v.d. Graaff unit; a beam output from the AGS could be 10^9 p/sec, U^{22+}, $T_N \lesssim 2$ BeV/n; however, even for a e^{-1} particle transmission ratio (due to electron capture or loss in the accelerator) a vacuum pressure of $< 2\ 10^{-11}$ torr would be required, in addition to significant complexities of the rf acceleration system, since a frequency "swing" of a factor of ~ 40 would be involved. Alternatives, involving a tandem stage, as an AGS heavy ion injector, were ruled out for similar reasons. Subsequently, a more detailed study of ion electron capture or electron loss cross sections vs particle energy for various ion charge states led to the following approach for achieving heavy ions, $A > 200$, $T_N > 1$ GeV/n, intensity $\sim 10^9$ ions/sec: a) Use fully stripped ions, in the slow rise time (~ 0.5 sec) large $B\rho$ accelerator, b) obtain the fully stripped state ion (for U, > 100 MeV/n) with a fast rise time booster synchrotron, and c) use the highest charge state in the booster (commensurate with a reasonable magnitude of the preaccelerator stage) in order to sustain minimum transmission loss in the booster for a given vacuum pressure. The further justification for this approach will become evident below.

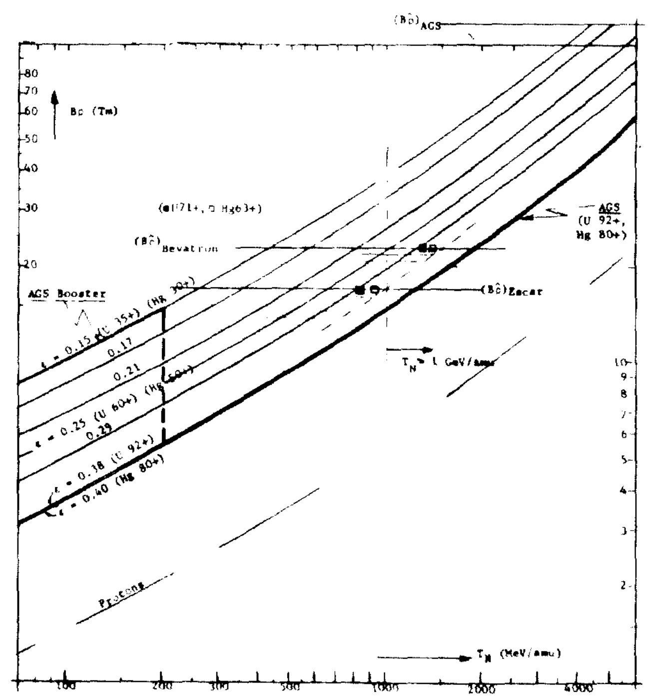

Fig. 1. Magnetic rigidity vs particle energy.

Particle Loss During Acceleration

Ion collisions with the rest gas molecules within the accelerator vacuum envelope lead to capture or loss of one or more electrons and consequently to loss of orbit stability in the accelerator, therefore result in particle loss during the acceleration process. In simplified form:

$$dN_{\text{charge exchange}} \propto N\,\sigma(\beta)\;\; \beta c dt \;\; n_g$$

resulting in $\quad (N/N_o) = \exp\left[-10^{27}\, P_{vac} \int \sigma \cdot \beta dt\right]$

where $\quad \sigma = \sigma_{capture} + \sigma_{loss}$, total charge exchange cross section.

A limiting aspect in the design of an accelerator system for heavy ions to high energy is the lack of experimental data for σ_c or σ_ℓ in the relevant range of ion energies. (The importance of this may be illustrated by the statement that a factor of 5 increase in σ_{tot} will change a 60% accelerator transmission ratio into a 6% transmission ratio.) A method has been developed to estimate the high energy charge exchange cross sections[5,6] the essence of which is as follows: In the process of passage through a dilute stripper, in the equilibrium state, it holds that

$$N(q+1 \rightarrow q)_{capt.} = N(q \rightarrow q+1)_{loss} \quad .$$

Ignoring multiple electron exchange processes, it follows that

$$F(q+1) \cdot \sigma_c(q+1) = F_q \sigma_\ell(q) \quad .$$

With the assumption of a Gaussian charge state distribution around the most probable charge state, $\bar{q}$, (ignoring shell effects and asymmetric distortions for $(\bar{q}/Z) \simeq 0$ or $\simeq 1$)

$$F_q \simeq d_g (2\pi)^{-1} \exp\left[-(q-\bar{q})^2/2d_g{}^2\right] \text{ with } d_g \simeq 0.32\; Z^{0.45} \; .$$

Consequently:

$$\sigma_\ell(q) = \sigma_c(q+1)\; \exp\left[-[2(q-\bar{q})+1]/2d_g{}^2\right] \quad .$$

This requires then-- $\bar{q}$ vs T_N (see Fig. 2) and σ_c vs T_N. For the latter relationship a scaling equation $\sigma_c \simeq q^2\ (\beta/2\alpha)^3\ \sigma_c$, (proton) has been proposed,[9] which, with experimental σ_c, (proton) data[10] leads to

$$\sigma_c(q) \sim 1.4\; 10^{-15}\; q^2\; (\beta/2\alpha)^{-6.6} \quad \text{where } \alpha = (1/137).$$

As a result, $\sigma_{tot} = \sigma_c + \sigma_\ell$ can be calculated, with the stated assumptions, as a function of the particle kinetic energy. (As an example, to illustrate the advantage of using the fully stripped ion state ($\sigma_\ell = 0$): σ_{tot}(U, 100 MeV/n, q = 30) = 5.6 10^{-17} cm^2; σ_c(U, 100 MeV/n, q = 92) = 4.8 10^{-20} cm^2).

U Acceleration in a Preaccelerator-Fast Booster-AGS System

As indicated in the foregoing it is desirable to obtain the fully stripped U state before injection into the AGS in order to ameliorate the vacuum pressure requirement in the AGS. This requires a prestripper particle energy of approximately 100 MeV/n. This can only economically be achieved with a fast rise time synchrotron booster stage. One (formerly) existing fast cycling booster synchrotron would be applicable here, i.e. the CEA 5 GeV electron synchrotron. This accelerator is now disassembled but its magnet system and ceramic vacuum system are kept in protective storage (because of residual activity) at the BNL site. Therefore,

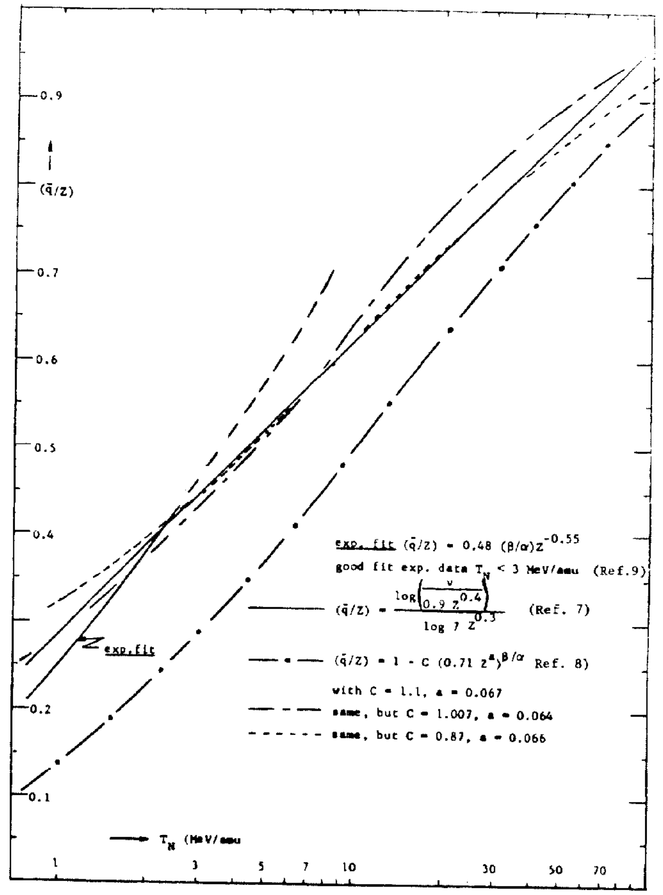

Fig. 2. Extrapolation $(\bar{q}/Z)$ vs T_N for U and a gaseous stripper (N_2).

the parameters for a booster-AGS system have been developed based on the availability of the CEA magnet system. Depending somewhat on the charge state after the first (solid) stripper following the preaccelerator, a smaller circumference accelerator than the CEA ring would be acceptable and actually advantageous in terms of peak rf voltage requirements and other cost related parameters. Therefore, a modified "CEA" lattice has been calculated, using 16 of the original 24 magnet cells, with an average radius of ~ 20 m (instead of R_{av} = 36 m) with only a minor penalty in transverse phase space acceptance. For a specific acceleration cycle, $\sigma \cdot \beta$ vs $\omega_c t$ (ω_c = booster cycling frequency) was calculated permitting the evaluation of $\overline{\sigma_{tot}\beta}$ over the acceleration domain and permitting the determination of the accelerator pressure "transparency". This is illustrated in Fig. 3 for the specific case of U, q=30, acceleration in the booster and in Fig. 4, for acceleration in the AGS. Other preaccelerator-booster combinations were considered, involving U, up to q = 40 charge state acceleration in the booster synchrotron (see Fig. 5). The overall results are summarized in Table I leading to the optimized parameters for U acceleration in the AGS as follows:

Preaccelerator: Ion source, U, q = 11+, 1 emA, 600 kV C-W structure; ≃ 10 m section Sloan-Lawrence or helix structure, exit energy ~ 0.75 MeV/amu.

Booster: Reduced radius (≃ 20 m, rather than 36 m), "CEA" fast cycling (30 Hz) synchrotron. Frequency range of system 1.7-24 MHz, $\hat{V}_{rf}$ ≃ 240 kV/turn. P_{vac} ≃ 4 10^{-9} torr. Ion charge state ≃ 35. Exit energy ~ 200 MeV/amu.

AGS: Rf requirements within range of existing system. P_{vac} ≃ 10^{-7} torr (≃ present value). Ion charge state 92. Extracted beam energy 1-10 GeV/amu. Intensity ≃ 10^9 p/sec.

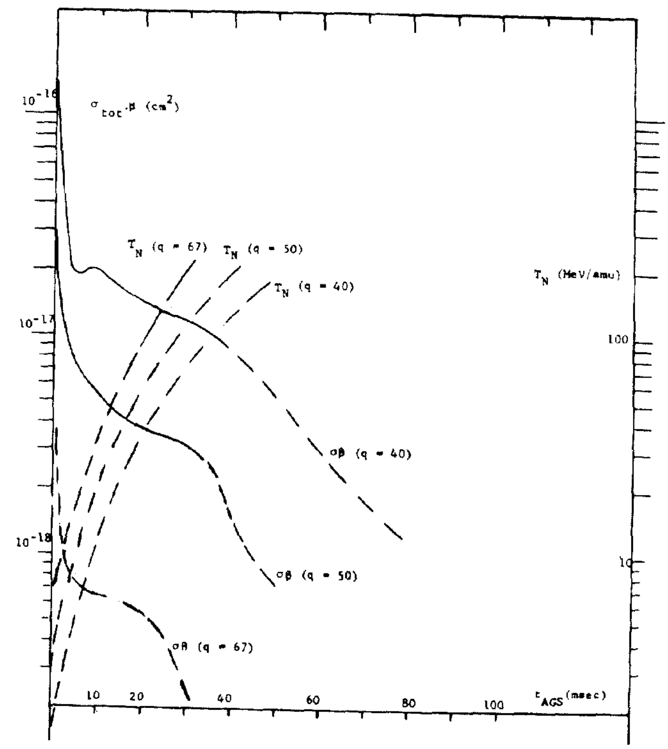

Fig. 4. Particle loss during acceleration. σ·β approximation vs time for acceleration in the AGS.

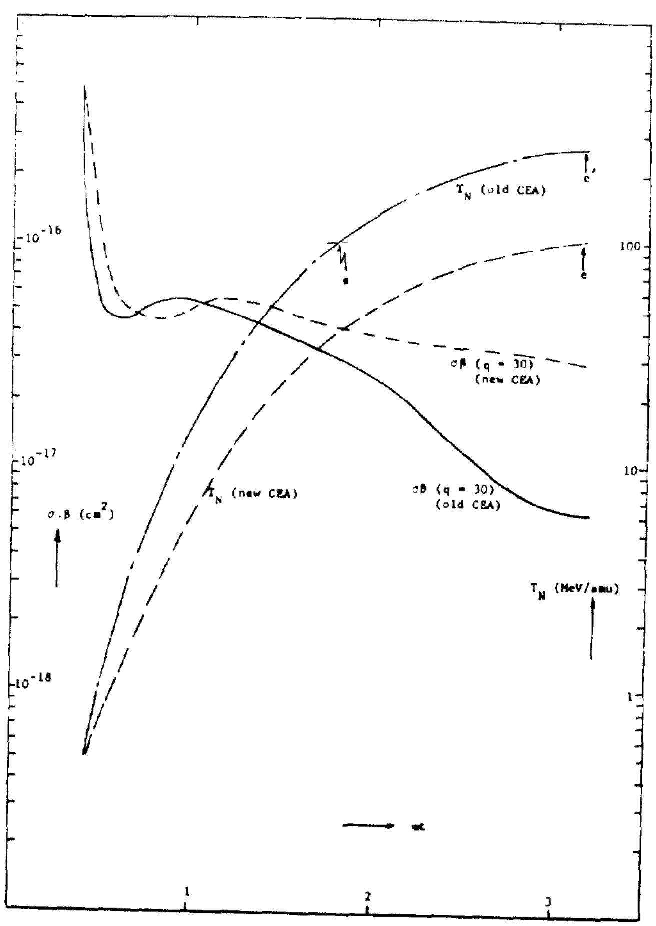

Fig. 3. Particle loss during acceleration and T_N vs ωt for the "old" and "new" CEA structure.

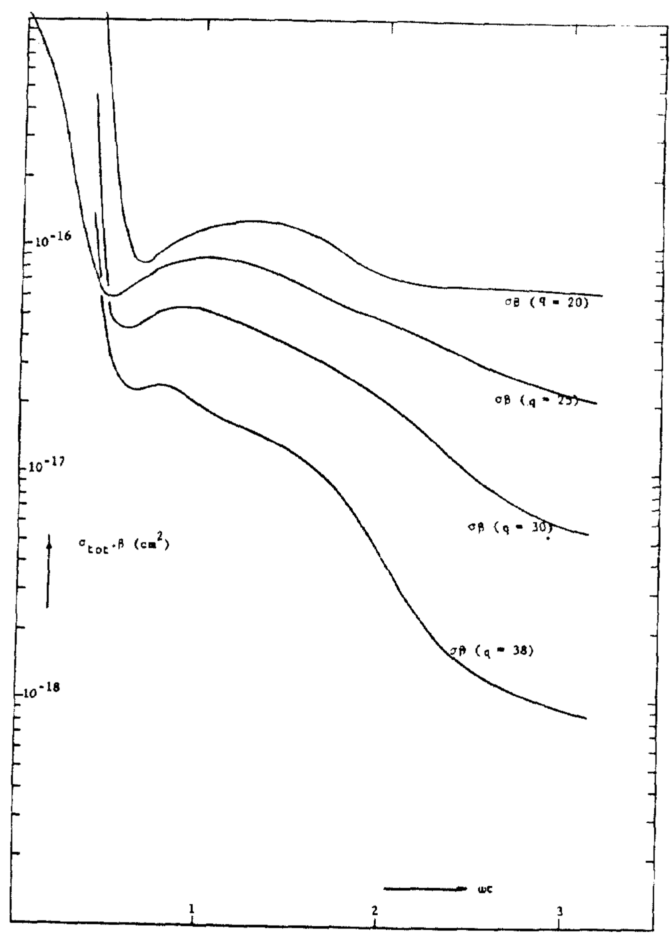

Fig. 5. Particle loss during acceleration in the booster (CEA unit).

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TABLE I - Parameters Preaccelerator-Booster-AGS System

							Speculative source
SOURCE							
equiv. volt.	MV	10.8	10.8	10.8	20	4	5.8
source	ion	U238	U238	U238	U238	U238	U238
	q	11+	11+	11+	11+	11+	38+
	emA	1	1	1	1	1	-
post strip	q	30+	30+	30+	38+	20+	no stripper
intensity	eA	$0.4\ 10^{-3}$	$0.4\ 10^{-3}$	$0.4\ 10^{-3}$	$0.52\ 10^{-3}$	$0.27\ 10^{-3}$	no attenua.
emit.	µrad-m	15π	15π	15π	11.2π	25π	no dilution
BOOSTER							
structure		"old CEA"	"old CEA"	"new CEA"	"new CEA"	"old CEA"	"new CEA"
T inj	MeV/AMU	0.50	0.50	0.50	0.925	0.184	0.924
β inj		0.0325	0.0325	0.0325	0.044	0.020	0.044
B inj	Gauss	306	306	459	494	279	494
n inj	turns	3	3	3	3	2	-
N capt.	p/p	$(4.6\ 10^{9})$	$(4.6\ 10^{9})$	$(3.4\ 10^{9})$	$(2.5\ 10^{9})$	$(2.5\ 10^{9})$	(-)
N sp.ch.	p/p	$2.1\ 10^{9}$	$2.1\ 10^{9}$	$2.1\ 10^{9}$	$1.8\ 10^{9}$	$1.5\ 10^{9}$	$1.8\ 10^{9}$
rep.rate	Hz	15	15	30	30	15	30
V max rf	kV	236.4	236.4	205.0	235.8	236.4	235.8
rf freq.	MHz	1.03 - 13.56	1.03 - 19.71	1.41 - 18.57	1.92 - 24.62	0.63- 13.56	1.9 - 24.6
harmonic	h	24	24	24	24	24	24
accel.range	ωt	π/8-1.75	π/8-π	π/8-π	π/8-π	π/8-2.5	π/8-π
$P\ vac^{*} \leq$	Torr	$1\ 10^{-9}$	$8\ 10^{-10}$	$1\ 10^{-9}$	$3.8\ 10^{-9}$	$5\ 10^{-10}$	$3.8\ 10^{-9}$
T eject.	MeV/AMU	100	260	100	200	100	200
B max	Tesla	(0.759)	0.759	0.669	0.765	(0.759)	0.765
$N\ out^{*}$	p/cycle	$8\ 10^{8}$	$8\ 10^{8}$	$8\ 10^{8}$	$7\ 10^{8}$	$5\ 10^{8}$	-
post strip.	q	92+	92+	92+	92+	92+	92+
inten.	p/cycle	$4.8\ 10^{8}$	$6.4\ 10^{8}$	$4.8\ 10^{8}$	$5.6\ 10^{8}$	$3\ 10^{8}$	-
emit.	µrad-m	1.5πx9π	0.9πx5.5π	1.5πx9π	1.1πx6.5π	3.4πx9π	-
AGS							
β inj		0.428	0.622	0.428	0.566	0.429	0.566
B inj	Gauss	449	752	449	650	449	650
n inj	turns	1	1	1	1	1	-
	cycles	4	4	6	6	4	-
N capt.	p/p	$1.5\ 10^{9}$	$4.1\ 10^{9}$	$2.3\ 10^{9}$	$2.7\ 10^{9}$	$0.9\ 10^{9}$	-
N sp.ch.	p/p	$1.2\ 10^{11}$	$3.9\ 10^{11}$	$1.2\ 10^{11}$	$2.8\ 10^{11}$	$1.2\ 10^{11}$	$\approx 3\ 10^{11}$
rep.rate	c/s	1	1.25	1	1.25	1	-
rf freq.	MHz	1.9-2.5	-	1.9-2.5	-	1.9-2.5	
V max rf	kV	~ 75	-	~ 75	-	~ 75	
rf freq.	MHz	2.5-4.2	2.8-4.2	2.5-4.2	2.5-4.2	2.5-4.2	2.5-4.2
V max rf	kV	avail.	avail.	avail.	avail.	avail.	avail.
harmonic	h	12	12	12	12	12	12
$P\ vac^{**} \leq$	Torr	$1.3\ 10^{-8}$	$1\ 10^{-7}$	$1.2\ 10^{-8}$	$0.7\ 10^{-7}$	$1.3\ 10^{-8}$	$0.7\ 10^{-7}$
N out	p/p	$1.3\ 10^{9}$	$3.7\ 10^{9}$	$2.1\ 10^{9}$	$2.4\ 10^{9}$	$8\ 10^{8}$	-
	p/sec	$1.3\ 10^{9}$	$4.6\ 10^{9}$	$2.1\ 10^{9}$	$3\ 10^{9}$	$8\ 10^{8}$	-
$T\ out^{**}$	GeV/AMU	2	2	2	2	2	2

* in Booster $(N/N_0) = 1/e$, in AGS $(N/N_0) = 0.9$.

** Maximum value in AGS ~ 12 GeV/AMU, at lower cycling rate.