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# Relativistic Heavy Ions at BNL--Ongoing Projects and Plans for the Future*

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## ABSTRACT

The AGS at Brookhaven National Laboratory is now being prepared to accelerate heavy ions up to mass 32 to energies of ∿ 15 GeV/A. Negative ions are to be made in a sputter ion source, accelerated in the BNL tandems to energies of ∿ 7 MeV/A, stripped of all electrons, and transported the 2100' to the AGS. Some considerations for the injection and acceleration of Tandem beams directly into the AGS are described as are future plans for the acceleration of heavier mass ions in the AGS and ultimately the acceleration of ions in a two ring collider (RHIC) to 100 GeV/A. The physics programs for which these accelerators are designed are briefly discussed.

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Construction has begun on an ∿ 2100' tunnel and transfer line connecting the Tandem Van de Graaff and the AGS at Brookhaven National Laboratory. With the linking of these two accelerators, heavy ion beams of $^{16}O$ and $^{32}S$ at a maximum energy of 14.6 GeV/nucleon will become available for experimental purposes in late summer or fall of 1986. The accelerated beam will be extracted from the AGS ring and transported to the present AGS experimental area. Proposals for the use of the beams are now being considered for approval by the Advisory Program Committee of the AGS in a similar manner to the usual proton beams. It is expected that there will be five weeks of heavy ion beam time in 1986 and ten weeks in 1987. The tandem heavy ion injection is a first step in a planned heavy ion accelerator complex (Fig. 1) which covers more than ten decades in collision energy and encompasses virtually all masses in the periodic table (Fig. 2). It is hoped that the entire facility can be completed by the mid 1990's.

The main interest in high energy heavy ion beams stems from the realization that the energy density of a nucleus is ∿ .16 GeV/fm$^3$ whereas the energy density of a free nucleon is approximately 3 times greater. If nuclear matter were heated and/or compressed sufficiently, it might be possible to allow the quarks confined in each of the nucleons of the nucleus to have "free" access to a much larger region of many fm$^3$ volume. The situation is shown in Fig. 3, a representation of the phase diagram for nuclear matter$^{1)}$. Normal nuclear matter exists at ∿ zero temperature and nucleon density, $\rho_{nm} = 1$ near the gas-liquid boundary. As the temperature and/or density of normal nuclear matter is increased, as it will be in a heavy ion collision, it is expected the system will move towards the quark deconfinement boundary indicated by the cross-hatched area. That this boundary is indeed a phase transition is borne out by QCD lattice calculations$^{2)}$. Two limiting trajections are easily distinguished. The trajectory, at low temperatures and increasing density, is the path believed to be taken by very dense stellar objects; whereas the trajectory at rarified density and high temperature is the trajectory taken in the early stages of the universe after the "big bang".

It is believed that each of these two trajectories can be simulated in the laboratory by collisions between heavy nuclei at high energies. The situation is shown schematically in Fig. 4. Before the collision, the two nuclei are approaching one another at high speed. In the center of mass, each is seen contracted along the direction of motion. At center of mass total collision energies of $\sim$ 5 GeV/nucleon pair (AGS energies), the nuclei interpenetrate but do not have sufficient energy to pass through one another and will deposit their total energy (kinetic plus mass) into a volume smaller than one nuclear volume[3)]. Since they are contracted in one dimension and since they stop, the energy density is increased to $\sim 2\gamma\rho_0$ where $\rho_0$ is the normal nuclear density and $\gamma$ the Lorentz factor. At AGS energies $\gamma \sim 2.8$ and densities $\sim$ 6 times normal nuclear matter are expected. At higher energies the nuclei are expected to be transparent to one another because the individual nucleus do not make enough collisions to come to rest. The two nuclei then interpenetrate and separate leaving a baryon poor region between them. A high density of particles, mostly pions, produced thermally from the Fermi sea of the QCD vacuum, is all that is left in the central region. It is this region of low baryon density and high temperature that can be explored in a heavy ion collider facility such as the RHIC collider for which a proposal is now being prepared by BNL.

Many signatures have been suggested to determine whether the conditions for producing the quark-gluon plasma have been attained. Among these signatures are: a limiting hadron temperature[4)] (as seen from the expoential decay of momentum spectra), enhanced products of strange antibaryons[5,6)], enhancement of lepton-pair production[7,8)], direct production of photons[7,9)], enhanced production of strange baryons and mesons[8)], scaling laws for various production cross-sections[7)] and the invariant mass of lepton pairs[8)]. Some of these signatures are presumed to be direct probes of the quark matter phase; others result from the way in which the quark matter phase is expected to congeal back into cold hadronic matter. All of them require careful systematic studies as a function of beam energy and projectile mass to identify with certainty. A "central" collision (zero impact parameter) at AGS energies between $^{32}$S and $^{197}$Au is expected to result in the emission of several hundred particles. The experimental equipment required to identify and sort these reaction products will be complex, large, and will utilize the utmost in sophistication in both data acquisition and detector techniques. For a further review of heavy ion physics at relativistic energies, the reader is referred to two recent conference proceedings10,11).

## TANDEM INJECTION INTO THE AGS12)

The tandem injection line to the AGS is to be constructed of warm quadrupole and dipole magnets and conventional double focussing, achromatic optics. The ∿ 2100' line is built of seperated sections of about 200' each, bringing the beam from a point focus to a point focus. Less conventional is the concept of tandem injection of a synchrotron13). Large pulsed currents from tandems have been recently demonstrated and make this alternative attractive14).

The current which the Tandem can inject into the AGS is determined by the emittance of the Tandem beam, the acceptance of the AGS and the intensity of the Tandem beam. The number of ions which can be stacked in the AGS is given by the ratio of the horizontal AGS acceptance (120π mm-mrad) to the Tandem emittance. As an illustration, consider an oxygen beam of 8 MeV/nucleon. The tandem emittance is ∿ 1.3π mm-mrad so that ∿ 90 turns could, in principle, be used. Since the tandem has produced instantaneous currents of $3 \times 10^{14}$ particles/sec and the circumference of the AGS is 807m, $\sim 5 \times 10^{11}$ particles could be injected. This current is greatly in excess of the experimental data handling capability and close to the space charge limit of the AGS. More reasonably, we expect to reduce the source current and inject only 10 turns into the AGS and have beams of $\sim 4 \times 10^{10}$

particles/pulse of oxygen (or carbon) and beams of ∿ 6.$10^8$ particles/pulse of sulfur. Table 1 gives some of the pertinent beam parameters.

As can be seen from Table 1, as the mass of the projectile increases the current available from the AGS becomes smaller. In fact, tandem injection into the AGS does not lead to useful beams for mass appreciably greater than sulfur. This fact comes from the requirement that only beams which are fully stripped can be maintained during acceleration because of electron stripping in the comparatively poor vacuum of the AGS.

The requirement that the injected beam energy be high enough to provide a sufficient number of fully stripped ions has given an added impetus for a proposal, submitted to the DOE, for a booster synchrotron between the Tandem and the AGS.

## BOOSTER SYNCHROTRON 15)

The booster ring is to be 1/4 the AGS diameter and is intended to serve the triple purpose of providing higher proton currents, higher polarized proton beam intensity, and of accelerating tandem beams of up to mass 200 to energies at which they can be fully stripped for further acceleration with AGS. The ring is to be located near the AGS as shown in Fig. 1 and is also convenient to the transfer line presently being built. The beam from the tandem is injected into the booster and stacked by filling the machine with ∿ 8 turns. The intensity of the beams up to the mass of copper will be limited by the Tandem current; above the mass of copper (for example for iodine and gold) the beams will be space charge limited (Table 2). At the end of the booster acceleration cycle the beam will be stripped and the fully charged beam injected into the AGS. Acceleration in the AGS proceeds in the ususal manner resulting in ∿ 11 GeV/nucleon for the energy of the Au beam. Since the poorest stripping efficiency is for the gold beams (40%), AGS currents $\geq 10^9$ ppp are anticipated for all masses. The cost of the booster is estimated at ∿ $25M in 1987 dollars and it is to be completed in 1988.

The physics motivation for the heavier ions at ∿ 15 GeV/nucleon (AGS energies) is very similar to that with the lighter direct tandem injected beams. The use of the heavier projectiles makes increasingly certain that the large energy densities required to produce the quark-gluon plasma can be obtained 16). With the heavier projectiles and their associated larger number of nucleus, the possibility of multiple scattering and of collective effects will increase for both the primary and secondary particles, and will result in a greater energy deposition in the nuclear volume. Since the bombarding energies are not large enough for the nuclei to be transparent to one another, the energy is more likely to be contained, thermal equilibrium established, and the liklihood that the quark-gluon plasma be formed is substantially increased.

## RELATIVISTIC HEAVY ION COLLIDER (RHIC) 17)

A proposal is being prepared to construct a relativistic two-ring heavy ion collider in the ∿ 3800m circumference tunnel built for the CBA project at BNL. As described above, the physics goals of this facility are parallel but different from the lower energy ones. Here the main aim is the production of the quark-gluon plasma in a state of high temperature and low baryon density which has been likened to the conditions shortly following the "big bang".

The facility will accelerate beams up to the mass of gold. The beams will be inititated at the Tandem, injected into the booster and then the AGS, and finally accelerated up to ∿ 100 GeV/nucleon in RHIC. Super conducting magnets (3.5T) contain the beam. Filling time per ring is to be ∿ 1 minute, acceleration time ∿ 1 minute with the storage lifetime of the gold beam (worst case) ∿ 10 hours. Four experimental halls are already constructed (one open and three enclosed); two more are available for future expansion.

The luminosity is a function of the energy and crossing angle of the beams. For zero crossing angle, there will be a maximum luminosity of $1.2 \times 10^{27} \mathrm{cm}^{-2} \mathrm{sec}^{-1}$ (gold ion beams). The interaction length is ∿ ±50 cm at zero crossing angle and

±14cm for a 2mrad crossing angle. Table 3 gives some of the beam parameters at the highest energy. At lower energies, the luminosity is reduced because of intra-beam scattering, particularly for the higher mass beams. However, since cross sections are ~ 10 barns for heavy ions, even a luminosity of $10^{23}cm^{-2}sec^{-1}$ is experimentally viable.

The RHIC accelerator will require five years to construct and cost ~ $135M.

## CONCLUSIONS

The immediate heavy ion project now funded at BNL will offer an exciting look into the new physics of nuclear matter under far-from-normal conditions. Hopefully, the first glimpse of the properties of the quark-gluon plasma will be obtained. In any case, a better formulation of the equation of state will result. Heavy ion beams of this energy have not been prepared before and the liklihood of new and altogether unsuspected results is always greatest in a totally unexplored region. The addition of the booster accelerator increases the range of projectile masses that can be accelerated in the AGS so as to include virtually the entire periodic table. The increased mass of the projectile will increase both the energy density and the volume of the high density material formed in the collision. If "glimpses" of the quark-gluon plasma at high baryon density can be observed with the lighter beams, systematic studies can be made with the booster beams. The basis of our knowledge of the equation of state of nuclear matter will be further broadened. With RHIC, the program enters an altogether new realm - that of the quark-gluon plasma at low baryon density and high temperature. It is here that the theoretical considerations are most definite and convincing, and the hopes for observing both phase transitions - the dissolution of the quark-bags and the restoration of chiral symmetry - are brightest. An entirely new region of exploration in fundamental physics will become available.

## ACKNOWLEDGEMENTS

Much of the information presented here is based on material contained in the proposals (references 12, 15 and 17) which describe three steps in the planning of relativistic heavy-ion facilities for Brookhaven. A large number of Brookhaven scientists and engineers have contributed to these proposals. In addition, the assistance, criticism and guidance received from other laboratories and universities has been of great importance.

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TABLE I. Beam properties for Direct Tandem - AGS Injection

| | OXYGEN | SULFUR |
|---|---|---|
| SOURCE INTENSITIES | 100 pμA | 200 pμA |
| TOTAL PULSE LENGTH | 220 μsec | 220 μsec |
| TANDEM STRIPPING EFFICIENCY | 30% | 3.7% |
| POST STRIPPING EFFICIENCY | 100% | 6% |
| AGS CURRENT | $4 \times 10^{10}$ ppp | $6 \times 10^{8}$ ppp |
| AGS ENERGY | 14.6 GeV/A | 14.6 GeV/A |

TABLE II. Beam Intensity From Booster (particles per pulse)

| Element | $N$ $\times 10^9$ * | $N_{sc}$ $\times 10^9$ ** |
|---|---|---|
| CARBON | 22.0 | 37.0 |
| SULPHUR | 6.7 | 11.0 |
| COPPER | 4.7 | 5.5 |
| IODINE | 3.4 | 3.2 |
| GOLD | 3.6 | 2.2 |

*With 8-turn injection

**Space charge limit for $\Delta\nu = .1$

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TABLE III. RHIC Initial Luminosity at Top Energy

| | E/A (GeV/amu) | Luminosity ($cm^{-2} sec^{-1}$) Crossing Angle (mrad) 0.0 | 2.0 | |
|---|---|---|---|---|
| PROTON | 250.7 | 1.2 | 0.28 | X $10^{31}$ |
| DEUTERIUM | 124.9 | 11.9 | 2.8 | X $10^{30}$ |
| CARBON | 124.9 | 5.8 | 1.4 | X $10^{29}$ |
| SULFUR | 124.9 | 4.9 | 1.2 | X $10^{28}$ |
| COPPER | 114.9 | 22.6 | 5.7 | X $10^{27}$ |
| IODINE | 104.1 | 6.7 | 1.7 | X $10^{27}$ |
| GOLD | 100 | 1.2 | 0.30 | X $10^{27}$ |

## FIGURE CAPTIONS

Figure I. Aerial view of the BNL site for the heavy ion complex. The transfer line from the Tandem to the AGS is in construction now. The booster synchrotron is proposed for completion in 1988. At the top, an arc is shown of the existing CBA tunnel proposed for a relativistic heavy ion collider.

Figure II. Heavy ion energies for existing, funded and planned facilities at BNL. The project now under construction (heavy line), will allow the direct injection of fully-stripped heavy ions from the Tandem into the AGS up to $^{32}$S.

The dot-dashed curve is derived from semiempirical charge-state formulas18) for low masses and energies. It is extended, with considerable interpolation, to recent values obtained for Au beams at the Bevalac19). Three stage tandem energies are required for $^{32}$S-beams while 2-stage energies are adequate for $^{16}$O-beams. For heavier masses, the booster synchrotron is required to allow the efficient stripping up to Au.

Au beams accelerated in the AGS can be injected into RHIC. The energy for RHIC beams is in the center of mass whereas laboratory energies are used for the other curves.

Figure III. Phase diagram for nuclear matter. $\rho_{nm}$ is the ratio of the matter density to that of cold nuclear matter. The expected region for a phase transition is shown by the shaded area. (from G. Baym, ref. 1).

Figure IV. Schematic description of the expected behavior of heavy ion collisions at high and very high energies. The colliding nuclei are shown flattened to emphasize the effect of the Lorentz

Figure IV. (cont) contraction. The middle illustration is appropriate at the energies provided by the AGS and booster; whereas the bottom one is for energies of a high energy collider such as RHIC. (Figure adapted from L. S. Schroeder, reference 11 page 359).

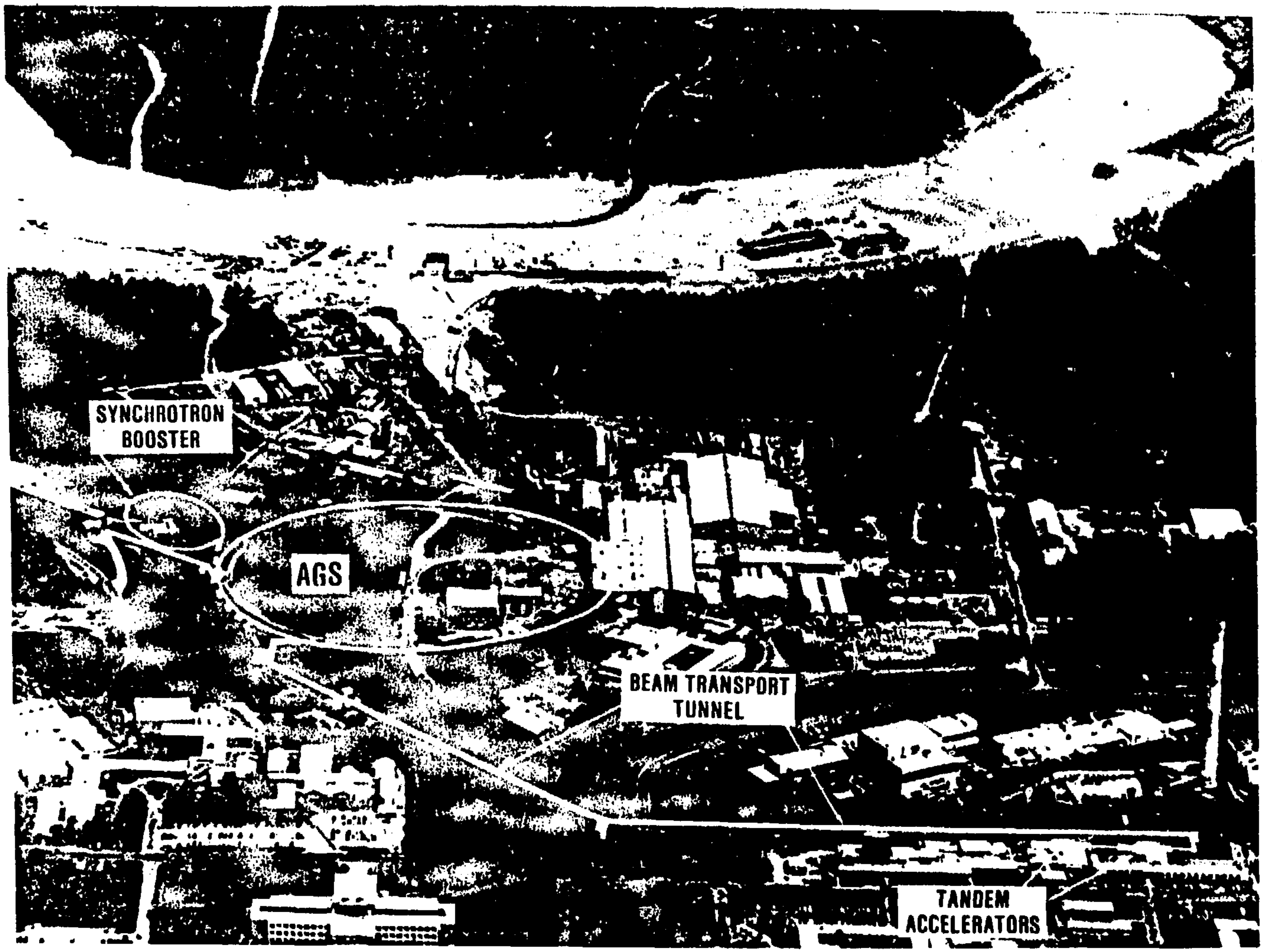

SYNCHROTRON BOOSTER
AGS
BEAM TRANSPORT TUNNEL
TANDEM ACCELERATORS

FIGURE I

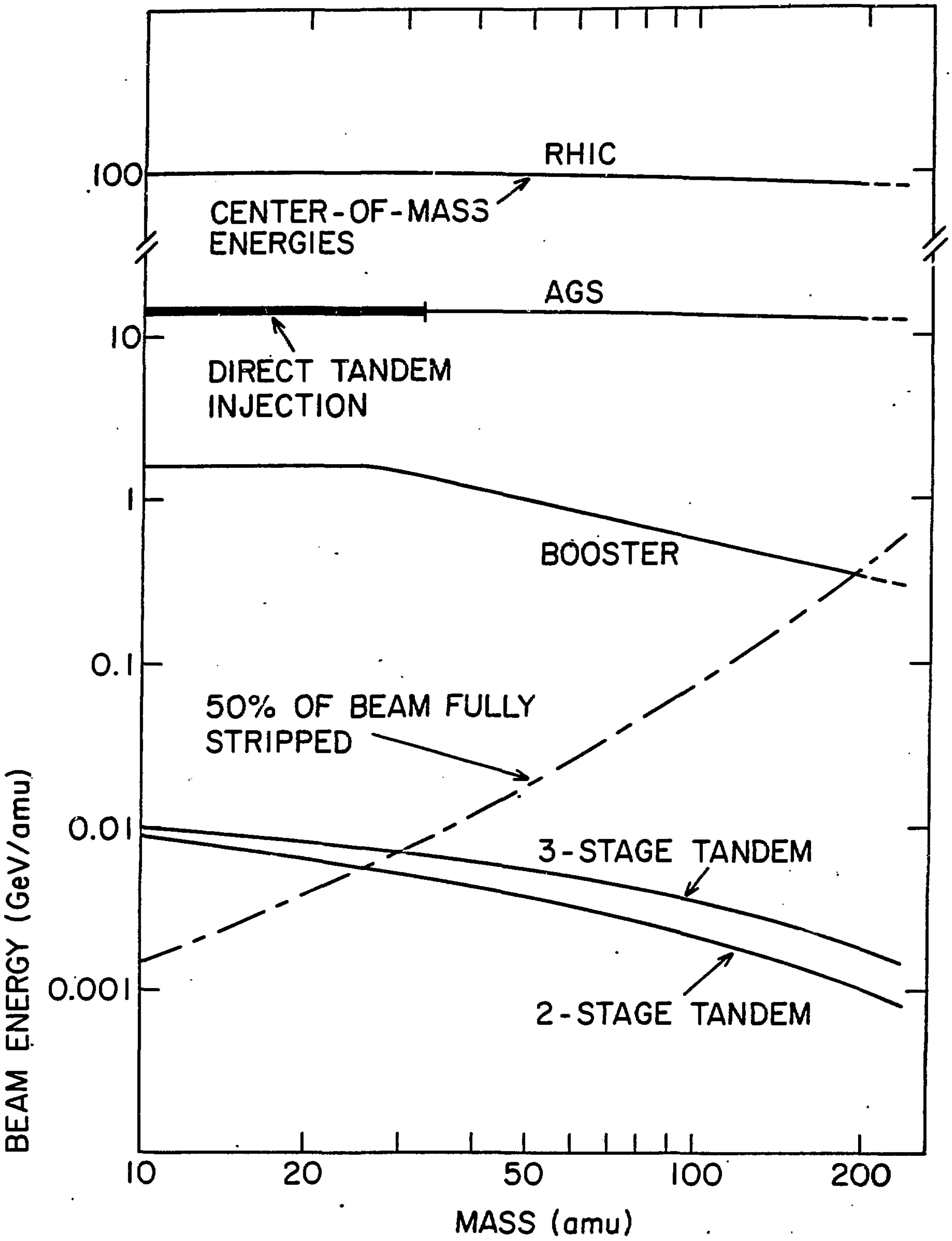

RHIC
CENTER-OF-MASS ENERGIES
AGS
DIRECT TANDEM INJECTION
BOOSTER
50% OF BEAM FULLY STRIPPED
3-STAGE TANDEM
2-STAGE TANDEM
100
10
1
0.1
0.01
0.001
BEAM ENERGY (GeV/amu)
10
20
50
100
200
MASS (amu)

FIGURE II

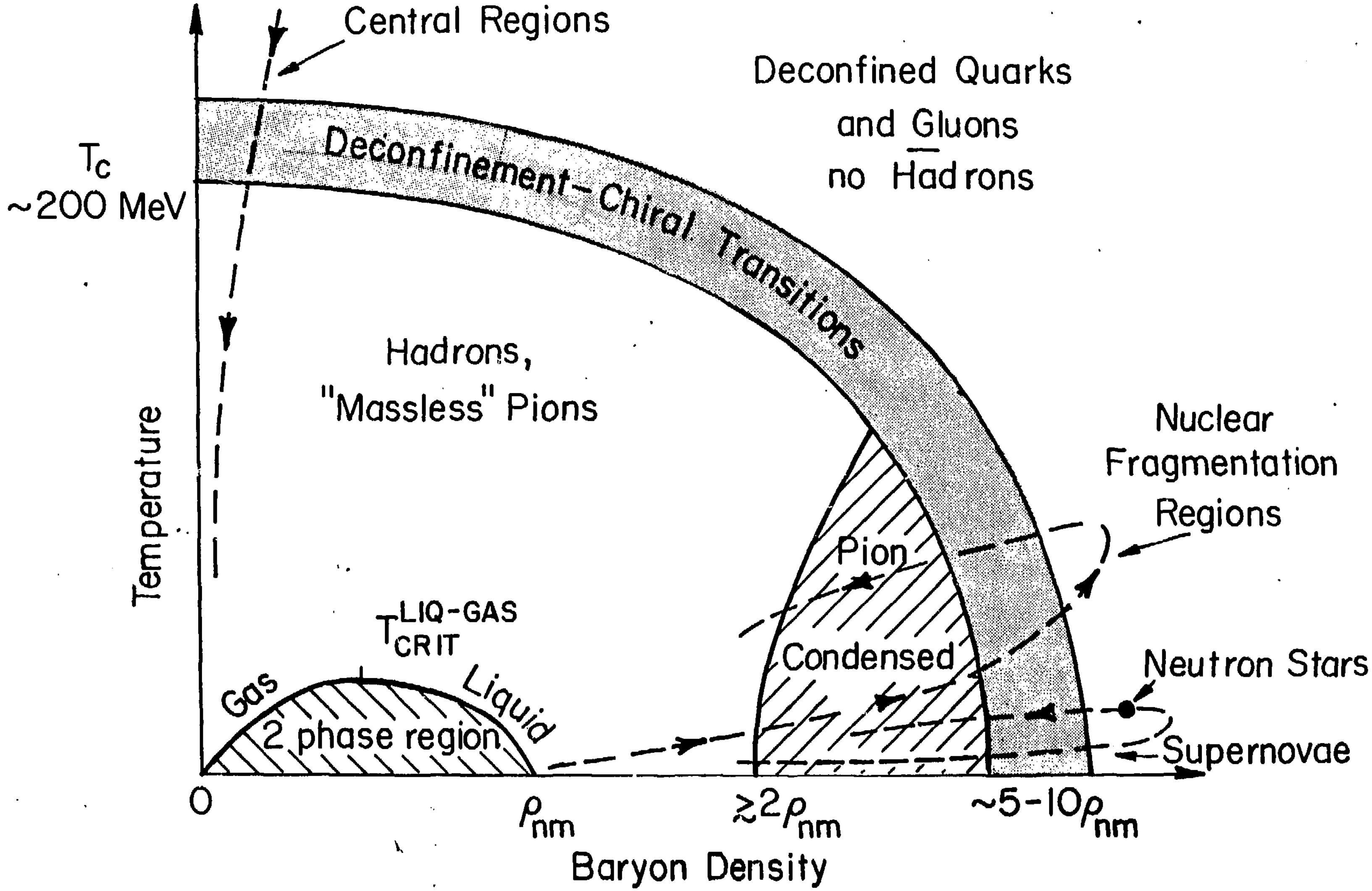
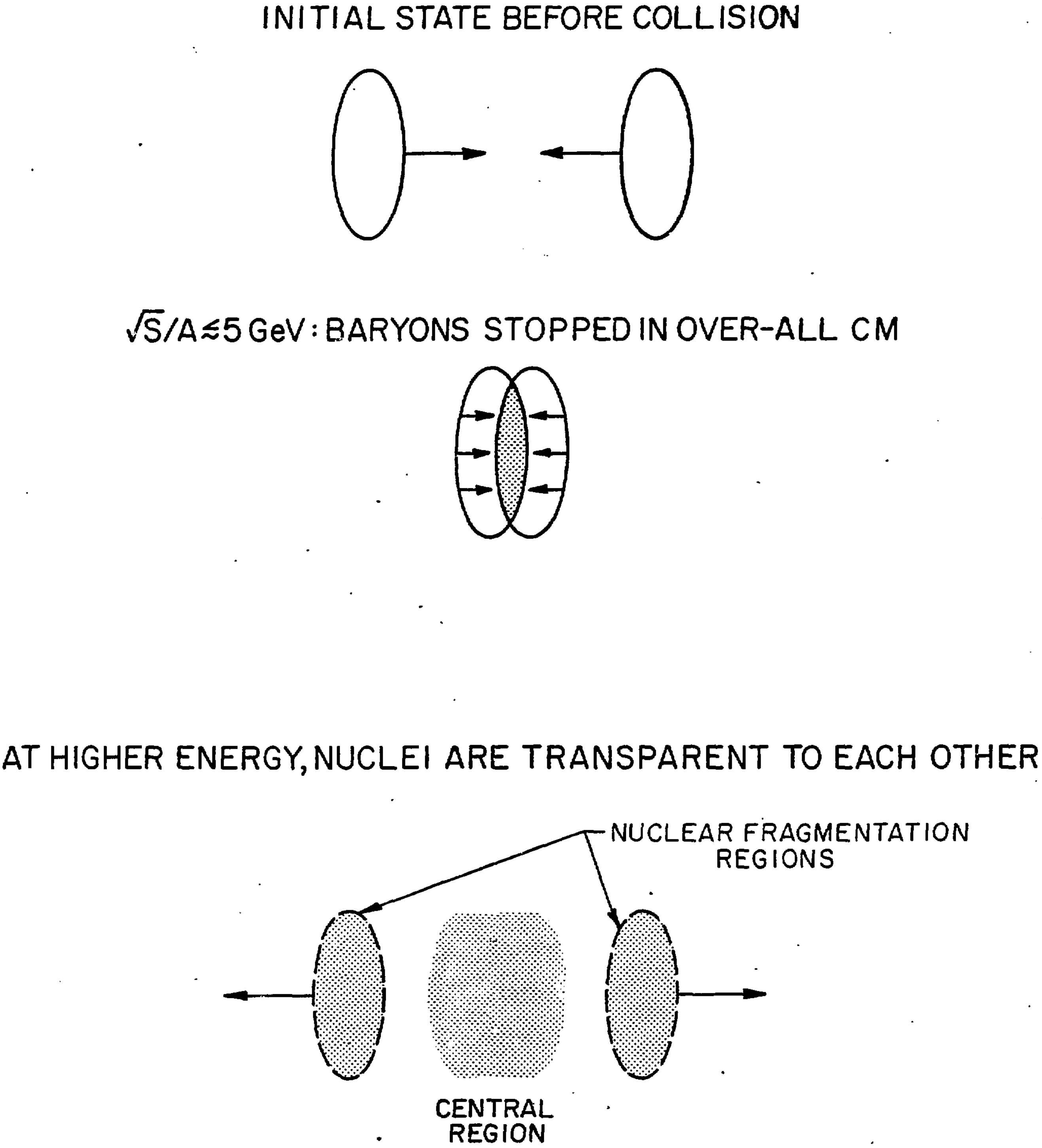

Central Regions
Deconfined Quarks
and Gluons
no Hadrons
$T_c$
~200 MeV
Deconfinement-Chiral Transitions
Hadrons,
"Massless" Pions
Temperature
Nuclear
Fragmentation
Regions
Pion
Condensed
Neutron Stars
Supernovae
$T_{CRIT}^{LIQ-GAS}$
Gas
Liquid
2 phase region
0
$\rho_{nm}$
$\gtrsim 2\rho_{nm}$
$\sim 5-10\rho_{nm}$
Baryon Density

FIGURE III



INITIAL STATE BEFORE COLLISION

$\sqrt{S}/A \lesssim 5$ GeV : BARYONS STOPPED IN OVER-ALL CM

AT HIGHER ENERGY, NUCLEI ARE TRANSPARENT TO EACH OTHER

FIGURE IV