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Report by

SUBCOMMITTEE ON HEAVY ION FACILITIES

of the

NUCLEAR SCIENCE ADVISORY GOMMITTEE

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PREAMBLE

In 1980, NSAC initiated formation of a Subcommittee on Heavy Ion Facilities whose primary purpose was to provide input from a cross section of heavy ion physicists on the implementation of the heavy ion component of the 1979 Long Range Plan for Nuclear Science. The Subcommittee began its work in January 1981; this is its report.

The Long Range Plan provided guidelines for the allocation of operating and capital funds among the various subfields of nuclear science. Its most immediate impact has been on the recommendations for new facilities and upgrading of existing ones. The main task of the Subcommittee was to assess how the spectrum of facilities has evolved since the inception of the Long Range Plan and which additional facilities, if any, would be needed over the next decade.

The recommendations for heavy ion science in the Long Range Plan were based on input provided by a distinguished panel chaired by R. Stokstad[†] (the "Stokstad Report"). This report already assumed the existence of the new accelerators at Michigan State University, Argonne (ATLAS), Oak Ridge and Stony Brook. It gave the highest priority to the upgrading of three additional facilities and lower priority to a larger new accelerator later in the decade. It forsaw essentially constant operating funds. These recommendations led to the recommendations by the Facilities Subcommittee of NSAC for upgrading of three additional university laboratories. Major concerns of our Subcommittee were the distribution of the remaining resources in terms of projectile mass energy capability, and the balance between universities and national laboratories.

The deliberations and, in consequence, the recommendations of this report were constrained by several boundary conditions, implicit in the charge from NSAC. These limitations are as follows:

i) The energy range was limited to the region below 1 GeV/amu. Thus all ultrarelativistic physics - necessarily very expensive - was left out of the discussion.

ii) All recommendations should be compatible with the resources allocated to heavy ion science in the Long Range Plan.

iii) Recommendations should be made regarding the needs for the field to achieve its most important goals and should not address specific facility proposals now in existence.

The membership of the Subcommittee represents a broad cross section of scientists working with the heavy ion field and outside, with four experimentalists active in the various energy and mass regions, two theorists and two experimentalists active in light ion and intermediate energy physics.

[†] Heavy Ion Nuclear Science: Opportunities and Priorities, June 1979, unpublished (R. G. Stokstad, Chairman).

I. INTRODUCTION

Heavy ion nuclear science is a field of great breadth and diversity. This is the natural result of the very large span in energy and projectiles which modern heavy ion accelerators are capable of producing. In the low-energy regime heavy ion nuclear physics extends the tandem physics which has traditionally had a strong base at universities. At the high energy end it uses large accelerators at national facilities and merges into high energy physics.

These widely differing energy regimes require a great variety of detection equipment, ranging from solid state detector telescopes to millon dollar multi-detector arrays and spectrometers. Accordingly, heavy ion physics can be done at small university laboratories and at large user oriented facilities. It is this great diversity of interests and demands on equipment which makes it mandatory, within severely limited budgetary constraints, to set priorities within the field. On the other hand, it is also unlikely that predictions about the development of such a diverse field over a decade will turn out to be accurate at any more than a qualitative level.

Heavy ion research in the United States developed its broad base in the decade of the seventies. In this period, the Superhilac and Bevalac at Lawrence-Berkeley Laboratory, and the double MP tandem at Brookhaven National Laboratory began to serve external as well as local users. At the same time the introduction of sputter sources for negative ions of almost any species turned all large tandems into heavy ion accelerators. New large facilities were initiated at Oak Ridge National Laboratory, Michigan State University and most recently Argonne National Laboratory, all of which will have large users programs. As the accelerators, and detectors have become more complex, it has become fiscally impractical to maintain a forefront facility at each laboratory where heavy ion physics is pursued.

By the mid-1980's when the machines now under construction come into service, it is clear that more than 2/3 of the experimental research in heavy ion nuclear science will be carried out in user mode. This will change the style of research to one long familiar to our colleagues in particle physics, and more recently, in intermediate energy nuclear science.

The study of the nucleus both in itself and as a prototypical quantum mechanical system is a complex scientific problem which will require an intense continuing effort well into the next century. It is therefore important to maintain an educational environment of requisite depth to attract and train enough future nuclear scientists for academic as well as research careers in the field. Moreover, an education in nuclear science followed by a career in other disciplines has been an important mechanism to strengthen the scientific and technical base of this country. Training in nuclear science should, therefore, continue at a rate several times higher than that needed to maintain the nuclear science manpower itself. New facilities now under constructions, such as those at Texas A&M University, SUNY-Stony Brook, or recently recommended at Florida State University, Yale and the University of Washington, are representative for the effort to make a reasonable investment in modern university facilities. One may hope that these will ensure an adequate student base for the field.

However, there is no escape from the fact that most planned forefront facilities in heavy ion research exceed the scale of the traditional university laboratory. The best distribution of resources between modern university-based facilities and truly national facilities has been of great concern to this Subcommittee.

The period since 1977, when NSAC came into being, has been one of intense facility construction. Some feeling for the rapid evolution of facilities can be obtained from a comparison of the situation in 1977, 1982 and 1987 as a result of construction activity already initiated. Figure 1 summarizes the available beam energy and projectile masses in the U.S. (solid curve) and elsewhere (dashed curve) at these five year intervals. In 1977 beams above 20 MeV/amu were rare and the German Heavy Ion Laboratory at Darmstadt (GSI) occupied a pre-eminent position, especially at high masses. Now, or in the near term, the new machines at Oak Ridge National Laboratory and Michigan State University will produce beams with energies above 50 MeV/amu up to mass 12, and more than 20 MeV/A up to mass 20, respectively. Furthermore, completion of present construction both in the U.S and abroad will, by 1987, greatly extend the range, from 20 MeV/amu to 200 MeV/amu.

The NSAC Long Range Plan of 1979 envisaged the future evolution of heavy ion research as a mature (i.e., essentially stable) major subfield of nuclear science which would receive approximately a constant 25% portion of the resources of the whole field over the next fifteen years. A major emphasis in the near term was placed on accommodating perturbations in operating support associated with the start-up of major users centers at Oak Ridge National Laboratory, Argonne National Laboratory and Michigan

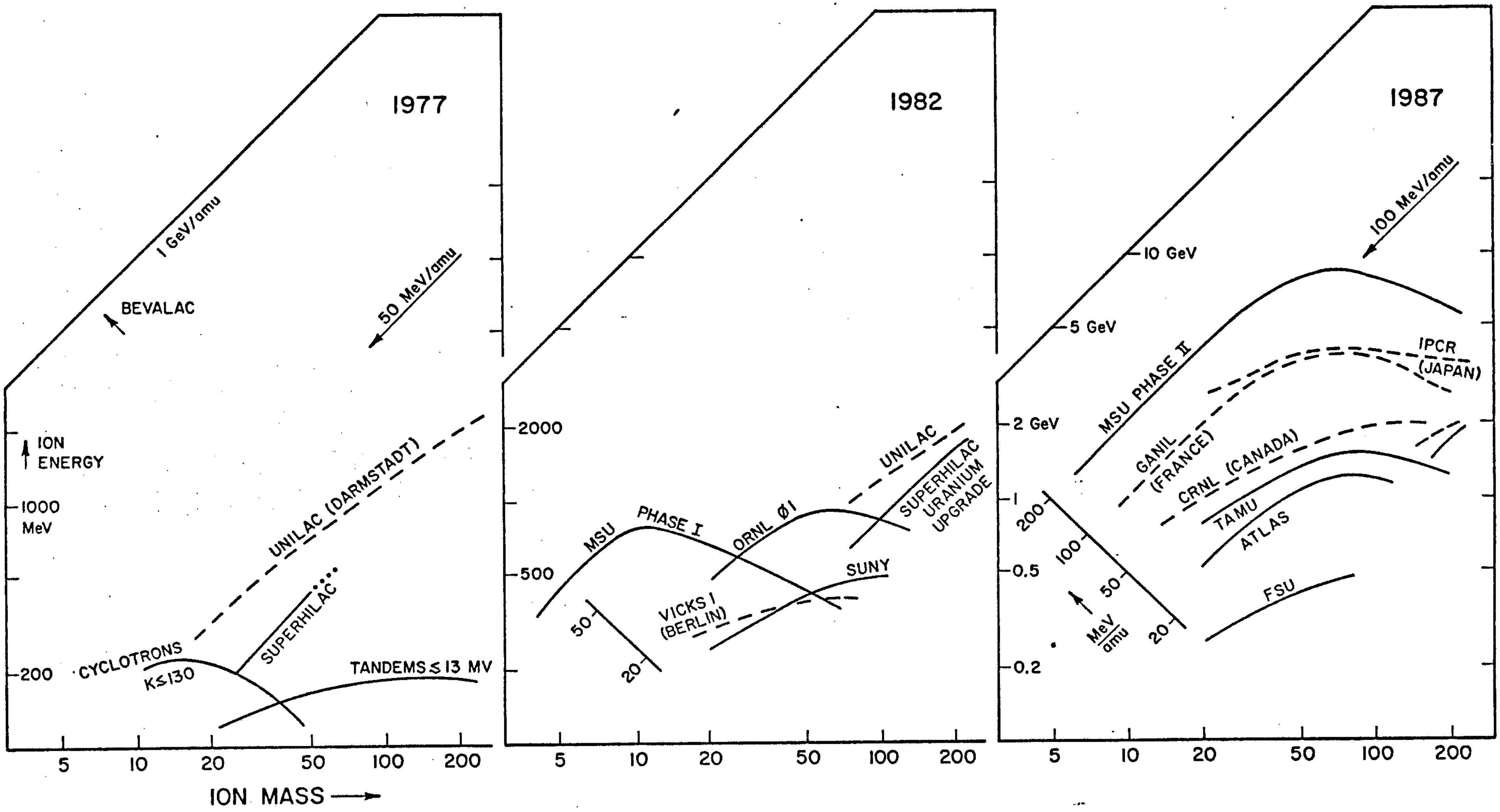

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Fig. 1 Schematic diagram of the evolution of heavy ion accelerators in the U.S. from 1977 to the completion of the present construction program.

State University, and on securing the future strength of the university-based heavy ion community by upgrading two or three tandems. The plan anticipated that future extensions of performance beyond the explicit plans within the framework of a constant level of funding could only be accommodated by redirecting resources from some less competitive facilities.

The question of the extent to which the rapid transition from in-house research to user's mode (from near zero to 60% in about one decade) could be allowed to continue was not settled in the Long Range Plan. It is clear, however, that redirection of resources presently expended in local (non-user) laboratories to create a new heavy ion user facility even of moderate size would swallow nearly all non-user funding in heavy ion science. The balance between a geographically and operationally diverse base, on one hand, and the focal facilities which carry the promise of exciting new development on the other, is a crucial question faced by the heavy ion community.

II. RECENT DEVELOPMENTS IN HEAVY ION SCIENCE

The Stokstad Report in 1979 presented a broad overview of heavy ion science and the most promising direction for its development. It is an impressive testimony to the breadth of the field. Fundamental questions in nuclear structure, nuclear reactions and the nucleus as a many-body system were opened to experimental attack. This basic outlook of promise and challenge has not changed over the last two years. In general terms, the early phase of qualitative experiments is changing to more systematic and precise experiments.

In the following we give a brief survey of recent trends in three major categories. We deliberately abstain from singling out any one item or experiment as "the singularly significant one" emphasizing instead the major advances that have been achieved and can be expected in all areas. The very broad contributions which heavy ion accelerators and detection techniques are providing for other disciplines, such as atomic and solid-state physics, are a matter of record and will not be detailed here. We refer in particular to the recent report on atomic physics with heavy ion accelerators.[†]

[†] Workshop on Accelerator-Based Atomic and Molecular Science, W.E. Meyerhof, editor; University of Connecticut Report U-46,1981.

A. Nuclear Structure Studies with Heavy Ions

1. Electromagnetic Properties

The most quantitative contributions of heavy ion physics to our knowledge of nuclear structure, so far, have come from the study of electromagnetic properties and transitions. Several unique characteristics of heavy reaction are relevant to these experiments: The high angular momentum produced in the reaction; the usefulness of fusion-evaporation reactions for the production of high nuclear excitations and of exotic nuclei far from the line of stability; the possibility of large recoil momentum permitting the spectroscopic study of short-lived isomers; the high Z of projectiles useful for multiple Coulomb excitation. Many of the experiments are optimized at energies near or slightly above the Coulomb barrier, at 5 - 10 MeV/amu. Thus studies of this kind are well matched to the several new machines soon becoming available which cover this energy range for all but the heaviest projectiles. For the high-energy recoil experiments which often use the heavier reaction partner as projectile, the Superhilac, the MSU Phase II and Texas A&M facilities and, up to A=130 ATLAS, are or will be available.

With heavy ion beams it has now become possible to probe the full range of excitation energy and angular momentum available to nuclei. Studies of "cold", or yrast, states up to spins as high as $40\hbar$ - using multiple Coulomb excitation or fusion-evaporation reactions - have revealed how the nucleus carries angular momentum most efficiently. Due to Coriolis forces, single particles play an important role at high angular momentum even in well-deformed nuclei. Successive breaking of pairs of high-spin particles and alignment of their angular momentum with the axis of rotation is now known to be responsible for the "back-bending" effect in yrast bands. When the ground states are spherical the high spin yrast configurations are predominantly aligned particle configurations producing oblate yrast states with a deformation gradually increasing with spins. In normally prolate nuclei calculations predict the possibility of the so-called giant back-bend, a drastic change in shape of the whole nucleus to a large prolate deformation. This becomes possible just before the nucleus becomes unstable to fission, but is still sufficiently stabilized by shell corrections. The nuclear behavior with changes in angular momentum near the fission instability will be a major area of interest.

Through the study of continuum γ rays in (heavy ion, xn) reactions, a beginning has been made to explore "hot" high spin states far above the yrast line. In prolate nuclei the excited continuum states appear to be similar in structure to the yrast states. However, in nuclei which are oblate along the yrast line the possibility exists that the nuclear shape changes gradually from oblate to triaxial shapes with increasing tendency to prolate deformation with increasing spin. Recent measurements of continuum γ rays from as high as 70 MeV excitation raised the possibility - still controversial - that giant resonances built upon a nucleus with high spin and temperature can be observed. Since much useful information about the nucleus as a Fermi liquid has come from the study of collective vibrations based on the ground state, the confirmation of such vibrations at high temperature would be very exciting.

Fusion evaporation reactions have been used to study systematically exotic nuclei well removed from the valley of stability, and to produce such nuclides for off-line measurements. Laser-induced spin alignment can then be used for direct measurement of quadrupole moments; laser spectroscopy of atomic hyperfine interactions has led to the discovery of a new region of deformation in the neutron deficient Hg isotopes. Deep inelastic scattering will be useful to produce exotic neutron rich nuclei.

The experimental possibilities for nuclear structure studies with heavy-ions have been greatly expanded by recent development in instrumentation and techniques. Multidetector NaI arrays and total energy γ detectors make it possible to isolate a well defined region in excitation energy and spin of the excited nucleus. The introduction of the γ-γ coincidence technique to the study of continuum γ rays has produced a wealth of data and makes it possible, for the first time, to determine actual collective (rather than effective) moments of inertia, even far above the yrast line, at high nuclear temperatures. If recoiling heavy ions are made to traverse certain foils with high velocity they experience extremely large transient magnetic fields (>100 MGauss). This effect has been utilized to measure magnetic moments of very short-lived high spin states both along and above the yrast line thereby providing a clue to the roles of neutron and proton orbitals. Finally, the entire area of interaction between laser beams and exotic or excited nuclei will experience a great impetus from the introduction of high-intensity ring lasers.

2. Particle Spectroscopy

Particle spectroscopy with heavy ions of energy comparable to nuclear binding energies is a field still in its formative stage. This type of reaction is the most effective one at our disposal for drastic rearrangement of many nucleons within a nucleus. Some promising developments have occurred within the last two years and this line of research will receive a major impetus as the new generation of heavy ion accelerators with high-quality beams becomes available.

We have some first evidence that simple modes of excitation are produced in heavy-ion reactions. Resonance-like behavior has been observed in heavy ion systems much heavier than before and at much higher energy. For instance, in the system $^{28}Si+^{28}Si$ containing 56 nucleons, "resonances" were seen up to excitation energies of $\sim$100 MeV. The origin of these regular structures constitute one of the major puzzles in nuclear physics today. The most exciting possibility is that they signal the existence of states of unexpected stability at extremely high excitation energies in the composite nuclear system. At the most fundamental level the observation of narrow structures in the continuum previously led to the discovery of states of a special symmetry (e.g., isobaric analog states) or states of unusual shape (e.g., fission isomers). The variety of ion species available together with the good energy resolution and variability of some of the new heavy ion accelerators will be instrumental in this research.

The description of direct reactions in terms of simple one-step processes, so successful with lighter projectiles, becomes more complicated in heavy-ion interactions as several degrees of freedom are closely coupled. The connection of these couplings with resonances and with fusion of projectiles into a compound system, or with strongly damped "deep inelastic" scattering, is one of the intriguing questions in understanding heavy-ion reactions and their interface with nuclear structure. The transition to the higher-energy behavior of heavy-ion reactions is still understood very poorly.

Light ion direct reactions transferring one or two nucleons have been an extremely rich source on one- and two-particle degrees of freedom in nuclear structure. Earlier hopes that light heavy ions could be similarly useful by transferring single nucleons into high spin orbitals have been revived by recent results in deformed nuclei.

Perhaps of greater interest is the possibility of massive transfer. It has been demonstrated in the last two years that such transfer does occur on the pre-equilibrium time scale. In analogy with the light-ion reactions, one can then hope that the direct transfer of clusters would provide a connection with the symmetries involved in heavy-ion resonances.

A final area awaiting systematic data is high resolution inelastic scattering. Particular interest here is centered on the possible excitation of high spin giant resonances, such as 4^+ and 5^- modes. Since early experiments with light ions suffered from fragment break-up background, heavier projectiles could be more successful and, indeed, first results are quite intriguing.

In the transition region between 10 and 50 MeV/amu, new effects due to high energy density and the high nucleon density produced in heavy ion reactions may be observed. The study of this region near the Fermi energy awaits experimental data.

B. Heavy Ion Reactions at Energies Up to 20 MeV/amu

Until recently this area of study was dominated by the Unilac at Darmstadt and the Superhilac in this country. The beams from both machines have relatively poor beam energy resolution and time structure. The new accelerators under construction now, and already operating at Oak Ridge National Lab, will be of great help, but in the U.S. only Michigan State University II will provide a needed capability for the heaviest ions.

1. Deeply Inelastic Collisions

Early studies have mapped out the bombarding energy and projectile-target mass combinations for which deeply inelastic processes dominate, as well as the qualitative features of the inclusive one-particle momentum distribution and energy damping. Emphasis during the past several years has concentrated on attempting to elucidate the specific mechanisms by which energy damping is achieved. This has not been an easy task since many of the observables in deeply inelastic collisions are expected to be similar for rather different energy dissipation mechanisms. The two principal mechanisms which are expected to contribute to energy dissipation are excitation of collective degrees of freedom due to the time dependence of the Coulomb and nuclear potentials during the collision, and dissipation due to exchange of nucleons between the interacting nuclei. With respect to the former mechanism, calculations have shown that considerable energy can be pumped into low multipole collective vibrations. The primary uncertainties in such model calculations are the distribution of collective strength of the damping associated with these degrees of freedom. One signature of this process would be structure in the energy loss spectra at the energies of giant resonances. Possible evidence of such concentration has been presented but is as yet controversial. The rate of energy loss from nucleon exchange can be calculated from the flux of particles exchanged between the nuclei, which in turn depends on the size of the "window" connecting the two nuclei. Both the collective excitation and the nucleon exchange models can qualitatively reproduce the dependence of the energy loss on scattering angle. Both models predict that the transferred angular momentum is oriented primarily perpendicular to the reaction plane, and that the in-plane component of transferred angular momentum is concentrated nearly perpendicular to the recoil direction. Both of these features have been observed experimentally.

More definitive evidence for the importance of nucleon exchange in energy dissipation comes from the number of exchanged particles inferred from the widths of the charge and mass number distributions. The rate of energy loss and the magnitude and alignment of the transferred angular momentum can be related to the number of exchanged particles, independent of a precise knowledge of the details of neck formation and the absolute rate of nucleon exchange. Comparison with experiment reveals a nearly quantitative understanding of the relation between particle exchange and energy loss and angular momentum transfer. Inclusion of the effects of Fermi motion and Pauli blocking is essential to this understanding.

Since the widths of the charge and mass distributions provide compelling evidence that nucleon exchange has occurred, it appears that the major fraction of the energy dissipation must be attributed to this mechanism. It remains a challenge for the future to identify the role of collective excitations.

Intimately related to the mechanism for energy dissipation is the question of the time scales for equilibration of various degrees of freedom. To what extent does thermalization take place? There is now evidence from the total number of neutrons emitted by each fragment that the two fragments achieve equal temperature by the end of the collision. This is not expected on the basis of present formulation of the nucleon exchange model, which predicts a more nearly equal partition of the excitation energy between the two fragments in mass asymmetric collisions. It is clear that the mass asymmetry degree of freedom is itself not equilibrated; for most energy losses there is little drift of the most probable charges and masses away from that of the original nucleus. It has also been suggested recently that the angular momentum bearing modes may be thermalized. If the thermalized complex is approximated by touching spheres this model leads to a prediction of an in-plane fission fragment anisotropy opposite in sign from that expected on the basis of nucleon exchange models. This question is presently under experimental investigation.

The recent availability at the Darmstadt accelerator of heavy projectiles (A>85) with E/A of 12.5 MeV/amu has led to the observation of a new phenomenon: projectile splitting or fast fission of the projectile-like fragment. A number of earlier studies have shown that, for bombarding energies less than 8.5 MeV/amu, fission of the heavy collision partners is a sequential process, with no evidence of unusual fission properties which would signify the influence of the third particle on the fission process. At the higher energy, however, it appears that the projectile-like fragment fissions with higher probability than would be expected from the excitation energy and angular momentum imparted during a deeply inelastic collision. The high fission probabilities, the azimuthal angular distribution and the energy dependences all suggest a fast process influenced by the third particle. This is a very exciting result, since it indicates that a rather modest change in the bombarding energy per nucleon can lead to a dramatic change in the reaction process. This suggests that the energy region of a few tens of MeV/amu is a very fertile field for exploration with heavy projectiles.

2. Fusion and Fusion-Fission

At bombarding energies not too far above the Coulomb barrier, the fusion of heavy ions to form a compound system accounts for the dominant fraction of the total reaction cross-section. It is this process that is used to produce nuclei with high spin and excitation energy. But the mechanism of the fusion process and the nature of its competition with other reactions is of fundamental interest by itself. The detailed study of fusion cross-sections has revealed the existence of significant effects depending on nuclear structure and dynamics, such as large oscillations in the fusion cross-section as a function of energy and a apparently strong dependence of the maximum fusion cross-section on the nuclear structure of the colliding nuclei. These effects provide stringent tests of fundamental theories of heavy-ion collisions, such as the time-dependent Hartree-Fock method.

At higher energies, a limit to the fusion-evaporation cross-section due to fission of the composite system has been sought and a decrease in the fusion cross-section is indeed observed at the highest energies. However, onset of different reaction mechanisms, such as incomplete fusion, may also be responsible for this decrease. A better understanding of the fusion cross-section at high energy and the partitioning of reaction strengths among fusion and other processes as the bombarding energy increases are principal objectives of future work.

A simple one-dimensional potential trapping model based on trajectories with proximity forces and energy dissipation from one-body dissipation has been quite successful in accounting for the average qualitative dependencies of fusion cross sections on bombarding energy and target-projectile charge products. One puzzle, however, has been the measurement of fusion cross sections which imply a maximum angular momentum larger than that for which the fission barrier is expected to vanish. Recent experiments, however, have indicated that for several mass-asymmetric systems at high bombarding energy the fusion cross sections are much reduced if one takes into account the loss of mass, energy and angular momentum carried away by pre-equilibrium particle emission. For heavier projectiles there is also some evidence that yield which had been previously attributed to fusion-fission processes is more likely to arise from deeply inelastic scattering with considerable drift along the mass asymmetry coordinate. There are, however, systems like ^{27}Al+^{208}Pb and ^{50}Ti+^{208}Pb at 5-6.5 MeV/A where a distinct symmetric fragmentation peak is observed in the mass spectrum with a yield much larger than would be expected for fusion-fission for ℓ values below the $B_f=0$ limit.

Detailed and successful theories exist which describe the fission of nuclei at low energies and low angular momentum. To date, however, there has been relatively little work which tests these theories at large angular momentum. The ability of the new accelerators to provide a variety of heavy ion beams with good energy variability over a wide range is crucial in these studies. With this ability, for example, a compound nucleus can be formed with different angular momenta at the same excitation energy, or vice-versa, and the fission process studied as a function of angular momentum or excitation energy.

As the fission decay of medium weight nuclei occurs only at extremely high angular momentum, fission measurements may provide a sensitive probe of nuclear structure or nuclear interactions at high angular momentum, beyond the region where discrete or even continuum γ-ray studies are useful. For example, a collective shape transition occurring at high angular momentum which results in a discontinuity in the yrast line of a fissioning nucleus may be reflected in the fission yields due to a changing competition between fission and light particle emission.

C. Collisions at Intermediate and Relativistic Energies

Almost ten years have elapsed since the beginning of research with relativistic heavy ion beams which began with perhaps too great an optimism for discovering new phenomena concerning nuclei under extreme conditions. In the last two years, the field has matured and developed, both theoretically and experimentally, to a point where it is clear that such effects will require very precise measurements to separate them from more prosaic and abundant background processes. There is now a substantial increase both in the complexity of experiments designed to measure exclusive quantities, and in the refinement of theoretical predictions. Over the last two years the first exploratory experiments at intermediate energies from 20 to 200 MeV/nucleon have also begun at the Bevalac and at the CERN Synchrocyclotron. These studies are important for extending the large body of knowledge of low energy heavy ion collisions, below 10 MeV/nucleon, into new regions, and also to trace the beginning of the new phenomena often associated with relativistic energies.

A key concept of relativistic heavy ion physics is the separation of the reaction products into participants and spectators. The participants constitute the overlapping portions of the nuclei in collisions, whereas the spectators are the residual parts sheared or abraded from target and projectile. The existence of these zones is consistent with present cascade and hydrodynamical calculations.

It was recognized very early that the spectator process might provide a snapshot of the ground state motion of the abraded fragment in the parent nucleus and experiments show that unique nuclear structure aspects might be accessible in peripheral relativistic collisions.

The identification of the spectator process appears possible down to at least 30 MeV/nucleon. In future experiments it will obviously be of interest to discover how this reaction mechanism develops from low energy deep inelastic scattering. Below 10 MeV/amu, these strongly damped collisions have taught us about the relaxation times of various degrees of freedom, such as energy, angular momentum, mass asymmetry and neutron to proton ratio. By making the reaction time shorter than the equilibration time, it will be possible to test the present transport and mean field theory in new situations.

The production of reaction residues with a wide range of N and Z in relativistic heavy ion collisions has another utilitarian aspect. It has been shown that the spectator fragments are a copious source of nuclei far from stability, because thick targets and almost 4π detection geometry are practical. Experiments now underway at the Bevalac to measure lifetimes and decay modes of such exotic nuclei will provide input for testing theoretical mass relations and astrophysical theories. It is likely that these experiments hold the greatest hope for reaching the limits of stability of light nuclei. Intermediate energies of 50 to 100 MeV/nucleon may be ideal, as they capitalize on the larger intrinsic production cross sections of the deep inelastic process while maintaining the detection efficiency of higher energies.

Finally, in our discussion of the spectator fragments, we mention the recent discovery that some fraction ($\sim$6%) of projectile fragments have an anomalously short mean free path in emulsions ($\sim$10 times smaller than expected). Such observations were already claimed in early comic ray studies, but only the recent accelerator-based experiments have the statistics necessary to quantify the effect. Possibly these observations imply the creation of a new state of matter which, by requiring a lifetime in excess of 10^{-10} sec and a force range three times normal radii of nuclei, would be very exotic indeed. Work at intermediate energies will be necessary to establish possible threshold behavior.

Turning to experiments on more central collisions, one of the fundamental objectives of relativistic heavy ion studies is the equation of state of nuclear matter, which involves the measurement of the energy per baryon, W, as a function of density and temperature. A related goal is the search for new collective degrees of freedom and phases of nuclear matter at high temperature and density. Theoretically, pion condensation, density isomers and even quark plasma states could be produced at sufficiently high densities. According to cascade model calculations, densities are attainable up to three times that of normal nuclear matter at 500 MeV/nucleon, albeit only for about 10^{-23} seconds. It is an open question whether these short times and the limited volumes involved in the collision will be sufficient to generate striking phenomena .

It is by no means obvious how W can be deduced from the experimental data or what the signatures of a phase transition would be. The basic reaction mechanisms in relativistic collisions are now known to be rather complicated, although high multiplicity data and extensive model calculations have sorted out many of these details quantitatively.

Hydrodynamical theories are now used to calculate the maximum pressure P and entropy per baryon, S, in the participant zone. Compared to the energy density $W(\rho,T)$ these variables are more directly related to experimental observables. The pressure, as the driving force for the fluid motion, determines the mean collective flow, whereas the entropy determines the hadron production rates and the proportions of light nuclear fragments. Regarding the pressure P, some experiments with a high multiplicity trigger bias toward central collisions indicate large transverse momentum transfers of light particles and to heavy fragments. These effects appear to be in qualitative agreement with hydrodynamical predictions and are larger than can be accounted for in cascade calculations. With the plastic ball and wall apparatus under construction at the Bevalac, the determination of triple differential cross sections $d^3\sigma/dE\,d(\cos\theta)d\theta$ may serve to verify the in-plane and out-of-plane jets predicted by hydrodynamics.

In principle the entropy created in the participant zone can be deduced from the hadron production rates and the ratio of light fragments such as d, t, ^{3}He and α. The simultaneous determination of P and S could remove ambiguities inherent in the determination of W. In the not too distant future, both experiment and theory may be sufficiently precise to determine the equation of state.

The above arguments rely, of course, on a hydrodynamical approach to heavy ion collisions, the validity of which has not yet been clearly established. Calculations indicate that the greatest sensitivity to the equation of state is obtained at low and intermediate energies of 50-100 MeV/amu. Below 50 MeV/amu it is unlikely that hydrodynamics will be relevant because of Pauli blocking. An important task at intermediate energies is to understand the transition region in which the mean free path is too short for the mean field description and too long for hydrodynamics to be valid.

The size of the participant zone can be derived from a comparison of single nucleon and complex particle production. In a thermodynamical model with thermal and chemical equilibrium, the production is determined by the volume in which thermodynamic equilibrium is maintained, the dimensions of which can then be deduced. Detailed studies from low through intermediate to high energies and comparisons of light and heavy particle induced reactions will be both necessary and instructive in sorting out the role of single nucleon versus fully thermalized processes. In the thermodynamical model, the ratio of deuteron to nucleon production is related to the entropy of the equilibrated system. A comparison of the experimental value with the theoretical expectation is one of the best indicators of new degrees of freedom in the hot, dense medium of the fireball. The excess entropy in the first comparisons with experiment was tentatively taken as evidence for new degrees of freedom such as pion condensation or dissociation of nucleons into quarks. Since the studies of collisions at intermediate energies have established a similarity to the basic high energy processes, the ratio of deuterons to protons might also be used to establish the entropy in conditions where all participating degrees of freedom are more fully understood. In fact, initial results indicate an almost constant d/p ratio (within a factor of 2) over several decades in energy. It may well be that factors other than entropy govern this ratio.

Another indication of an anomaly comes from observation of sideways peaking in angular distributions of α-particles and protons in reactions from 400 MeV/amu-2.1 GeV/amu. These peaks, which are reminiscent of Mach angle shock waves, disappear in the vicinity of 2.1 GeV/amu, an effect which is expected in the presence of a phase transition.

Signatures of coherence have also been sought in the pion emission spectrum. Theoretical studies of pion condensation indicate that in the system Ne+Ne, a small bump (1 mb/GeV^2) might be superimposed on the 90° invariant pion cross section at a transverse momentum $\simeq 2m_\pi$. At energies of 1 GeV/amu the background due to incoherent processes is three orders of magnitude greater, only by going to energies near 100 MeV/amu would the two contributions become comparable. Intermediate energies may, therefore, be more favorable to the detection of an exotic signal above the noise. Even if no break in the smooth exponential spectrum is discovered, a strong upper bound on the growth rate of pionic instabilities would be established. Experiments on pion production at low incident energy, down to 80 MeV/amu, are already in progress, and have yielded some interesting results for π^-/π^+ ratios, which can, however, be understood in terms of the conventional theory including Coulomb distortion of the pion wave functions.

The most pessimistic prediction of the outcome of relativistic heavy ion collisions - that the two nuclei would essentially be transparent to one another - does not appear to be borne out. Perhaps the most striking illustration of non-transparency comes from experiments which establish that the charged particle multiplicity distribution depends on the total projectile energy (independent of projectile) and not on the energy per nucleon, indicating that the projectile is brought to a complete stop in the target. On the other hand, experiments on elastic scattering of complex nuclei at intermediate energies indicate a high degree of transparency at least in the surface. The cross section predict-d by a Glauber model varies most strongly between 20 and 200 MeV/amu incident energy.

In the search for new phenomena there is a growing awareness of the importance of intermediate energies; this region may give the best signal to noise ratio for an exotic process. Intermediate energies may also be better suited to demonstrate the applicability of hydrodynamical approaches. In the region of 20 to 200 MeV/nucleon, many of the processes occurring at relativistic energies already seem to be well developed. The extension into this regime of the many phenomena observed in low energy heavy ion collisions will also provide new tests of low energy theories, of deep inelastic scattering, fusion, equilibrium and pre-equilibirum effects.

III. SCIENTIFIC EFFORT IN HEAVY ION PHYSICS

A. Manpower

In its 1979 survey of heavy ion physics the Stokstad Report estimated that about 25-27% of the nuclear research effort was directed toward heavy ion physics. This estimate was based on a survey of major universities and national laboratories, and on publications in major journals. The report concluded that the share of federal funding for nuclear science allocated to heavy ion physics, of about 33% at that time was reasonably well matched to the effort.

Since 1979 the scientific landscape has evolved significantly, in part because of new machines recommended by NSAC and since funded, and in part because of the phasing-out of two light ion facilities (Maryland and Stanford). Two major laboratories, TAMU and MSU with a total of 61 Ph.D research personnel, are dedicating themselves almost entirely to the use of heavy ions. Table I summarizes these changes since 1979. The accounting of FTE numbers in a consistent way between laboratories of very different sizes is a difficult undertaking. In addition, since several new accelerators are in various stages of completion, the users pattern is at present unsettled and probably not typical for the next few years. For these reasons we have chosen to present numbers for large categories: Major users facilities based at national laboratories, major user's facilities associated with universities (in the case of MSU this number involves only the in-house staff); and smaller university laboratories with an in-house heavy ion program. A more detailed accounting can be expected from the Manpower Subcommittee of NSAC. Even in these large groups a comparison between 1979 and 1981 numbers is subject to a significant error. However, it is probably accurate to

Table 1

Updating of scientific personnel in heavy ion research in three large catagories:

1) In-house and external users FTE at major national facilities with heavy ion capability; 2) two major user facilities based at universities; 3) university based laboratories with heavy ion capability. The 1979 numbers are from the Stokstad Report. The 1981 numbers have been obtained from personal inquiry by the Subcommittee and from recent progress reports and proposals.

	Total Ph.D		Heavy Ion Research	
	'79	'81	'79	'81
National Laboratories[1)]	192	173	167	147
Major University Facilities[2)]	69	59	10	32
Smaller University Facilities[3)]	152	139	83	93
	412	371	260	272

1) Bevalac, Superhilac, 88-in Cyclotron at LBL, BNL, ANL, ORNL
2) IUCF, MSU
3) Rochester, Yale, Univ. of Washington, Stony Brook, FSU, Cal-Tech, Pittsburgh, Penn, Rutgers-Bell, Texas A&M, Stanford, Maryland and Princeton

compare the ratio of heavy ion effort to total effort in each year. This ratio is 0.63 for 1979, and 0.73 for 1981. Although this increase is not large, it indicates a continuing shift from light ion (tandem) physics to heavy ion physics.

The same increase in effort is obtained from a survey of major journals. Late in 1980, Auerhach et al.[†] repeated their survey of all major journals, first done in 1978. A count of Physical Review C and

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[†] Survey of U.S. Heavy Ion Effort, E.H. Auerbach, A.J. Baltz, J. Barrette, L.E. Thorn, BNL 1980, unpublished.

Physical Review Letters yields 155 (134 in 1978) heavy ion papers out of 462 (433) papers, a ratio of 34% in 1980 vs. 31% in 1978. A survey of Physical Review letters 44/45/46 indicates that 35% of all nuclear physics papers address heavy ion physics. In hysical Review C 22/23/24% of all papers related to heavy ion physics. This statistic indicates that heavy ion physics is in the forefront of nuclear science. The number of individual co-authors increased from 507 (1979) to 619 (1980), a 22% increase, in very good agreement with the increase estimated above. The absolute number of authors is explained quantitatively with the assumption that each FTE Ph.D researcher has 1.2 graduate students associated with his research.

The average number of authors per paper gives some indication of the number of collaborators involved in any given experiment. From Physical Review Letters 44/45/46 the average is 7 authors per experimental paper. If we assume that these publications represent the technological edge, we may conclude that a modern experiment involves the participation of 7 people. (The largest number found is 11, the smallest 5). This estimate is supported by personal experience. Dividing the number of people in the field by the number of collaborators gives about 88 active groups.

Even if we assign to each group the minimum time of four weeks of beam per year, leads to a total beam time demand of 354 weeks. This demand is satisfied by about 9 accelerators at 40 weeks of beam time per year. This consideration does not take into consideration the different characteristics of accelerators needed for different experiments.

B. Facilities

Table II lists university-based facilties which are either operational now or under construction, or have been recommended by NSAC. Machines which have less than an equivalent accelerating voltage of 12 MV have been omitted (all stand-alone FN and EN tandems). Although machines below this level will continue to provide valuable data, they would not be able to participate in the study of the new regimes of projectile mass and energy. This leaves six facilities of which only the one at TAMU has an extended range in energy and mass. MSU is listed again as a national facility in Table III.

Included in Table II are numbers for the in-house research staff and the average number of graduate students claimed by each laboratory. A more detailed accounting of the total student level including user's operation is given in the Stokstad Report. It adds up to 126 students in 1979.

It may be noted that the only university-based facilities with extended mass and energy range, MSU and TAMU, both have large numbers of in-house users.

We specify for each accelerator the energy it can produce for a light, medium and heavy projectile. A measure of the limitation in the range of ions for which an accelerator is useful, is given by the heaviest projectile which can be accelerated to the Coulomb barrier, 5 MeV/amu. It is apparent that few installations exceed mass 100 in this regard. A second useful energy benchmark is 30-40 MeV/amu, the region of the Fermi energy. ATLAS and ORNL with ORIC reach this

Table II

University-Based Facilities with Major Heavy Ion Capabilities

Institution	Accelerator	Capability	In-house staff	Status	Supporting Agency
FSU	9 MV Tandem + 12 MV LINAC	^{16}O 8.5 MeV/amu ^{58}Ni 5.9 "	11 Ph.D 8 students	Recommended not yet funded could operate in '84	NSF
Rochester	13 MV tandem	^{16}O 7.3 MeV/amu	12 Ph.D 8 students	Operating	NSF
Stony Brook	9 MV tandem + 20 MV LINAC	^{16}O 13.5 MeV/amu ^{58}Ni 8 " ^{98}Mo 5 "	10 Ph.D 8 students	Under construction Operating in '82	NSF
U. Washington	18 MV tandem	^{16}O 8.6 MeV/amu ^{56}Fe 5.4 "	14 Ph.D 14 students	Recommended not funded	DOE
Yale	20 MV tandem	^{16}O 12 MeV/amu ^{40}Ca 10 " ^{74}Ge 5.0 "	11 Ph.D 20 students	Recommended not funded	DOE
TAMU	K=400 SC cyclotron +K=160 RT cyclotron	^{16}O 38 MeV/amu ^{116}Sn 10 " ^{208}Pb 5 "	30 Ph.D 16 students	Under construction from state and private funds, could operate '84	DOE NSF
MSU	K=500 SC + K=800 SC cyclotron	See Table III	31 Ph.D 24 students	Under construction should operate '86	NSF

Table III

National Heavy Ion Facilities

Laboratory	Accelerator	Capability	Status
ANL ATLAS	9 MV Tandem + SC LINAC	^{16}O 26 MeV/amu ^{98}Mo 16 " ^{165}Ho 5 "	Under construction Operational '84
BNL	12 MV + 17 MV Coupled tandems	^{16}O 12 MeV/amu ^{40}Ca 15 " ^{74}Ge 5 "	Operational, improvements under construction
ORNL ORIC	25 MV Tandem + K=100 cyclotron	^{16}O 25 MeV/amu ^{98}Mo 10 " ^{147}Au 5 "	Operational
MSU II	K=500 + K=800 coupled SC cyclotron	^{16}O 200 MeV/amu ^{116}Sn 150 " ^{208}Pb 40 "	Under construction Operational '85/86
(Chalk River*)	13 MV Tandem + K=520 SC cyclotron	^{16}O 50 MeV/amu ^{58}Ni 25 " ^{238}U 5 "	Under construction Operational '84
LBL Superhilac	RT LINAC	8.5 MeV/amu for all ions	Operational
LBL 88'' Cyclo.	K=160 Cyclotron	^{16}O 16 MeV/amu ^{40}A 5 "	Operational

*May be available to U.S. scientists.

regime for the lightest ions, but only MSU II and TAMU cover a wide range of masses; and only one facility comes even close to this region for the heaviest ions.

We conclude then that the accelerator spectrum is heavily concentrated in the lower mass range. All new machines which serve this mass region have good phase space and energy resolution, several have excellent energy variability. This beam quality which was not available before, will be instrumental in the exploration of the physics outlined in parts A and B of section II of this report. The accelerator with the broadest all around scientific interest, MSUII, has a large number of in-house users, a total of 55 Ph.D's and graduate students. Finally, it must be noted that the superhilac, one of the few accelerators which can produce a lead beam of some interest, has poor beam qualities and is a very power consuming device.

IV. MAJOR NEW FACILITIES FOR HEAVY ION PHYSICS ABROAD

The major European countries which emphasize nuclear research have already a long tradition in heavy ion physics. The scientific man-power directed toward heavy ions in West Germany, in absolute numbers, is about one half of that in the U.S. (if nuclear chemists and physicists are combined), while in France it is about one half of that of West Germany. Early on, each of these countries committed themselves to one large user's facility, GANIL in France and GSI in Germany. Each country had one additional smaller cyclotron facility, ALICE and VICKSI.

Now a number of new proposals are being developed for additional larger facilities. It is interesting to note that they are, with some exceptions, technically quite similar and aim at the same energy - projectile regime: 50-300 MeV/amu for the lighter projectiles, and 20-50 MeV/amu for $A \approx 200$. All consist of either single room-temperature (RT) or superconducting (SC) cyclotrons injected by a 13 MV tandem, or of two coupled cyclotrons.

Figure 2 (taken from a recent survey contained in an Orsay proposal) gives a schematic presentation of the various systems now under construction or, in the case of Orsay and Munich, proposed. Technically, the Munich proposal is the most exciting. It calls for a SC separated sector cyclotron with independent sector coils. It has already received funds for a feasibility demonstration of one coil.

The predicted performance and scheduled date of completion (in parentheses) for major accelerators presently under construction is plotted in Fig. 3 (from the 1981 Orsay Report). In addition to GANIL, SARA at

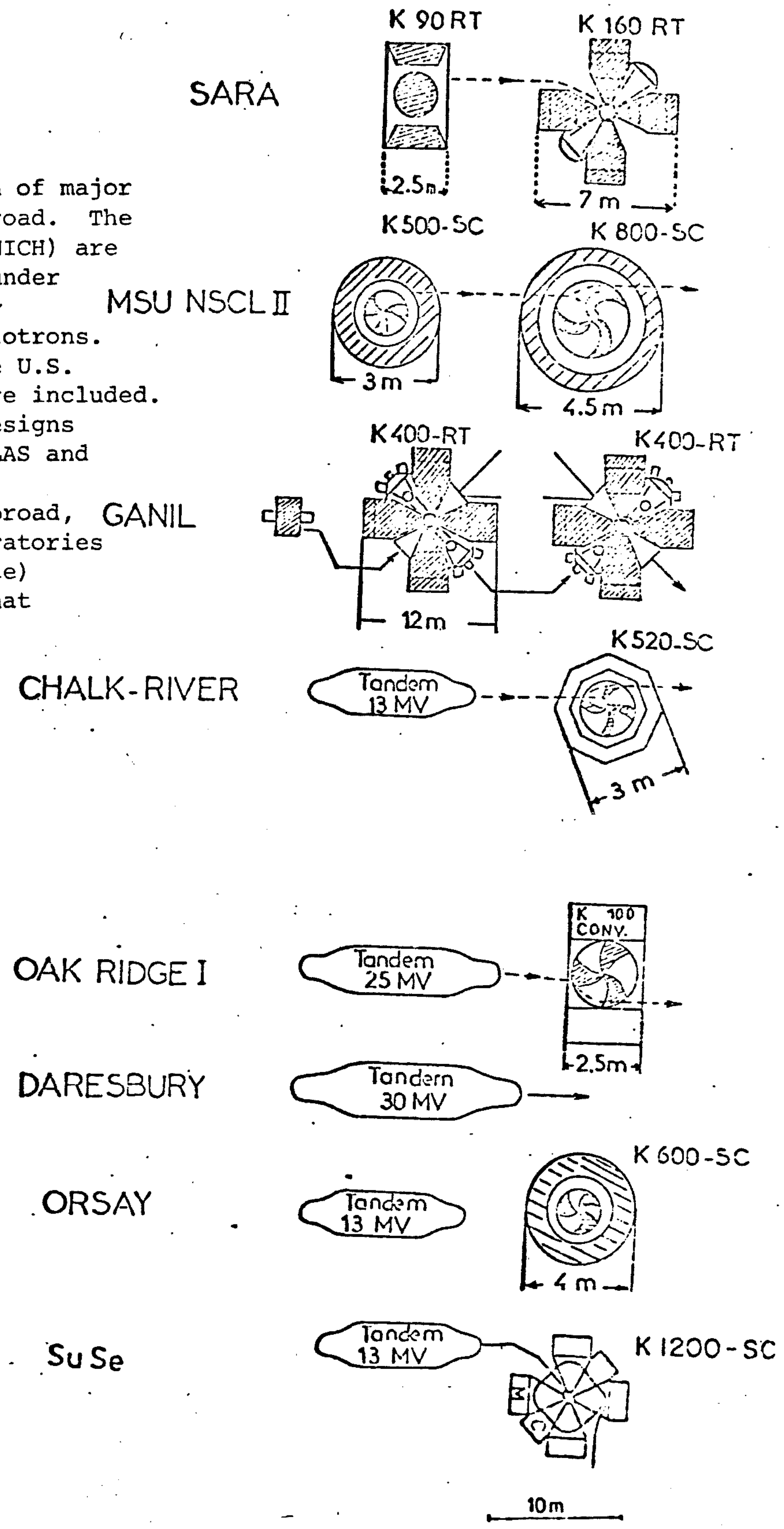

Fig. 2 Schematic description of major new heavy ion facilities abroad. The projects ORSAY and SUSE (MUNICH) are proposals. All others are under construction. Note that they essentially all involve cyclotrons. Therefore two representative U.S. projects using cyclotrons are included. The superconducting LINAC designs pioneered in the U.S. by ATLAS and Stony Brook have so far not induced similar proposals abroad, although several major laboratories (Canberra, Weizmann Institute) are making first steps in that direction.

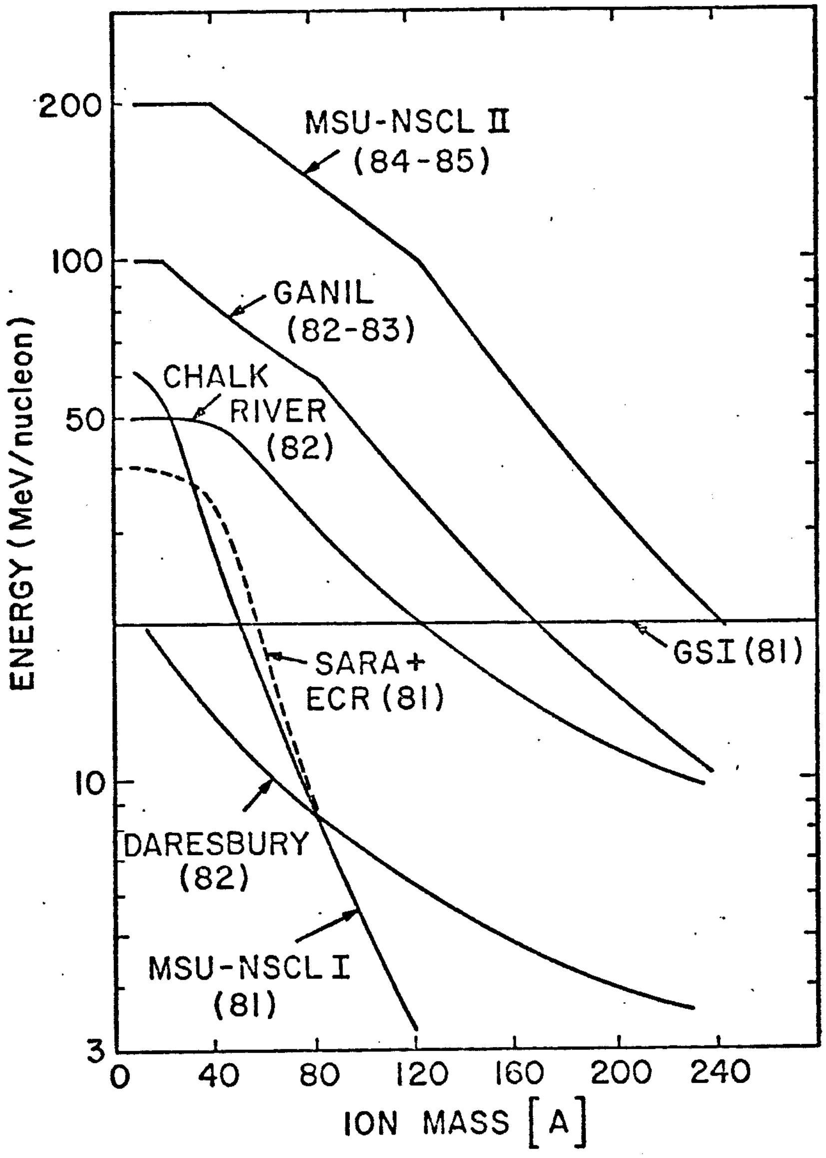

Fig. 3 Performance plot of some major heavy ion accelerators under construction (projected completion date in parenthesis) abroad with the MSU accelerator stages given for comparison.

Grenoble is nearing completion. Use of an ECR source is projected. The GSI LINAC is at present being upgraded to 20 MeV/amu for all projectiles. Finally, Fig. 4 gives a survey of some major proposals around the world. The uniformity in the perception of what performance will be exciting in the next two decades for heavy ion physics is demonstrated by this plot.

Not all of these proposals have a realistic chance of being funded. In West Germany, a commission on large nuclear facilities recently recommended against the Julich proposal but reacted favorably to the Munich proposal. If it is technically sound, this accelerator which follows MSU II closely in performance and cost (∿DM 80 millions) is likely to be built. With 20 MeV/amu for all beams available right now, the GSI LINAC will have a unique capability for U and Pb beams for several years to come, but the long term direction of GSI has not yet been determined. VICKSI in Berlin is being upgraded with a 8-MV tandem injector to produce 40 MeV/amu Ne beams and 10 MeV/amu for A=80.

In Italy the two 16 MV tandems at Legnaro and Catania are nearing completion. Apparently the Milan proposal to build a K=600 SC cyclotron following the MSU design, to be injected by either the Legnaro or the Catania tandem, is receiving funding.

Several cyclotrons, at Julich, Louvain-La Neuve and at Groningen have placed orders for ECR injector sources, and will shift emphasis to heavy ions.

We cannot assess the chances of the Orsay or the Strasbourg proposal to receive funds. The Orsay accelerator would obviously create a third large heavy ion facility in France. An effort to turn SATURNE into a 1 GeV/amu light heavy ion accelerator by use of an EBIS source has

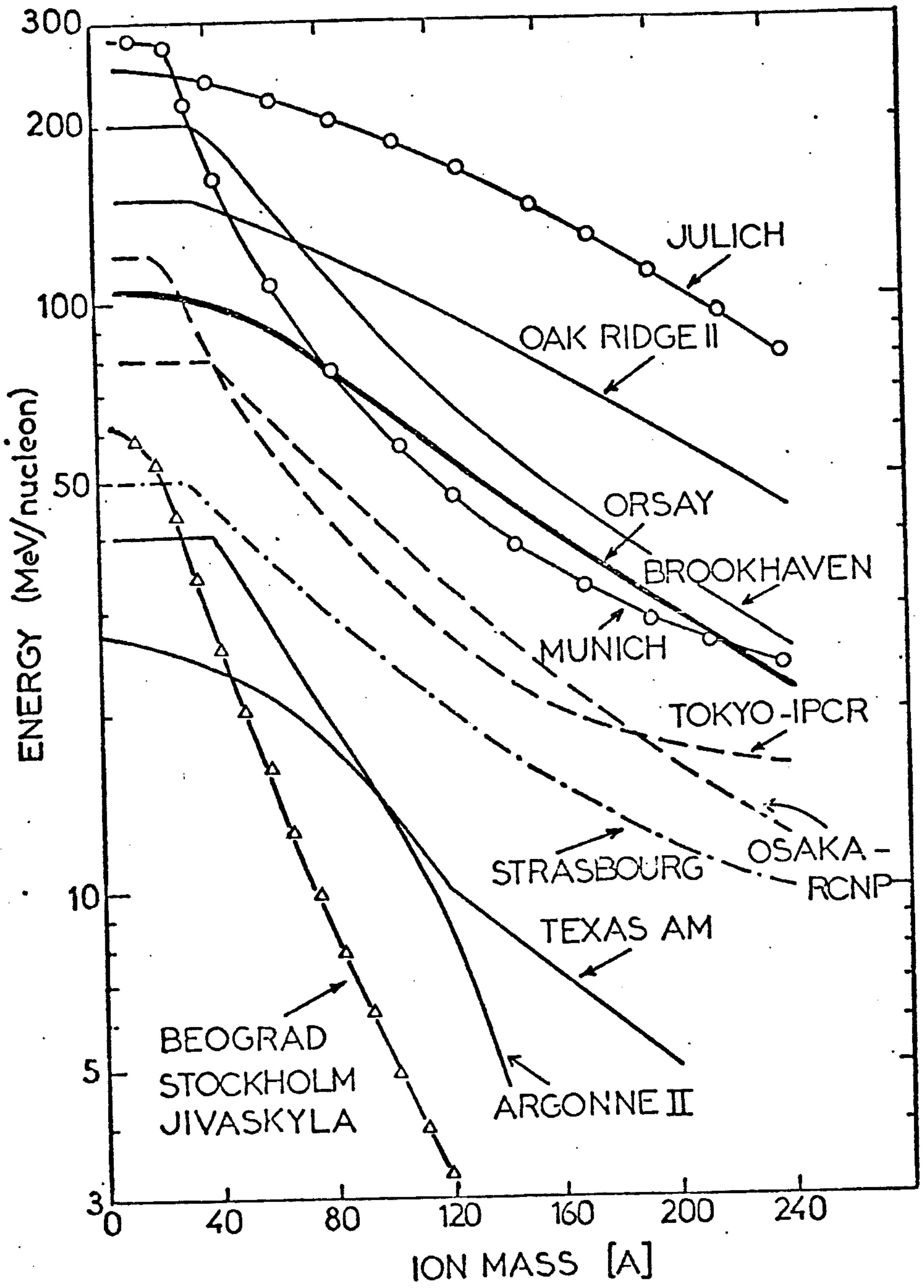

Fig. 4 Performance plot of recent major international and U.S. proposals.

so far not been successful. It is interesting to note that the only new proposal for a 1 GeV/amu accelerator which is essentially a copy of SATURNE, is justified and funded as a medical facility for radiation treatment. This is the project MARIA at the University of Alberta; the machine would be available for physics experiments part-time.

As in this country, perhaps even more so, heavy ion research in Europe has turned to the user's mode. Even major laboratories with an in-house capability and long tradition for heavy ion physics, like the Niels Bohr Institute or the Max-Planck Institute in Heidelberg, are heavy users of outside machines. On the other hand, MPI has been the first laboratory to develop a successful (20 MV equivalent voltage, room temperature) tandem-LINAC combination. Although the development of the superconducting LINAC in the U.S. is watched with close interest abroad, no definite proposal has yet evolved using this technology. A determined effort has been made to make use of the large CERN accelerators for heavy ion research. First experiments have been done with 86 MeV/amu carbon beams of excellent intensity and quality, at the CERN synchrocyclotron.

Although many of the smaller universities have suffered because of the concentration of funds in larger facilities, in many cases the large facilities have acted successfully as conduits for equipment funds to the user's home base. This has been a particularly strong program in the case of GSI and VICKSI. It is thus not surprising that many European laboratories have been able to aggressively push new instrumental techniques. We mention the development of large and sophisticated multiwire gas detectors for heavy ions, the 162-element crystal ball at MPI and the plastic ball (which although constructed at LBL is essentially funded by GSI), the new magnetic spectrometers at Julich and Groningen, and last but not least, the French developments of ECR and EBIS ion sources.

V. DISCUSSION AND RECOMMENDATIONS

A. Summary of Prospects in Heavy Ion Physics

Nuclear structure studies with heavy ion beams below 20 MeV/amu are flourishing. New precise beams and new instrumentation will continue to produce insight into the structure of the nucleus at extremes of angular momentum, temperature and deformation. Nuclear reactions will be able to study in detail the processes of energy dissipation and equilibration.

The region between 20-200 MeV/amu is expected to show rich and interesting transition behavior. Here the relative ion-ion velocities become comparable to several characteristic nuclear velocities. At about 35 MeV/amu above the Coulomb barrier the relative velocity is equal to the fermi velocity in nuclear matter. Below this energy the Pauli principle results in a long nucleon mean free path, so that the mean field is the main determinant of nuclear motion. Above this energy, the Pauli principle becomes less effective, nucleon-nucleon collisions become important and the mean free path decreases. The character of collisions is therefore likely to change qualitatively from the deep inelastic and fusion behavior of lower energies to the fragmentation and explosions observed at Bevalac energies.

Theoretically, this transition requires the modification of both the low energy mean field and the high energy cascade treatment. There is as yet no tractable formalism for smoothly interpolating between the two.

At these energies the relative velocities also become comparable to the velocity of sound in nuclear matter so that collective modes, such as the giant resonances, would be efficiently excited. Some theoretical estimates indicate that the best place to look for pion condensation may be about $E/A \sim 100$ MeV since collision times are longer than at higher energies and may give the pion field instabilities a chance to become more fully developed.

These may also be the best energies to look for hydrodynamical phenomena, such as shock waves and compression. At higher energies the diminishing importance of the mean field and the decreasing elementary nucleon-nucleon cross sections weaken the ion-ion coupling. Unusual non-equilibrium phenomena may become manifest due to collision times which are shorter than those at lower energies. Among these are the emission of fast jets of nuclear matter or the localized excitation of a nucleus.

The upper end of this energy region is just below the threshold for free nucleon-nucleon pion production. Studies of sub-threshold production might be used to probe high-momentum nucleons in the nucleus, or cooperative behavior involving clusters of several nucleons.

Finally, experience at lower energies indicates that macroscopic nuclear behavior does not become fully developed until rather large projectiles are used. We note that the center of mass correction for the heaviest projectile on the heaviest targets implies beam energies of between 50-70 MeV/amu just to cover the transition region.

CONCLUSION 1 - The low energy region from the Coulomb barrier to ∿20 MeV/amu is ready for exploration with high-precision heavy ion beams. A rich variety of new structural effects can be expected from such measurements, using high resolution instrumentation. With the longer view, we consider the beam energy region of between 20-200 MeV/amu as the most interesting one for the next decade. Experimental results of the last two years lead us to attribute less importance to the 200 MeV/amu to 1 GeV/amu region than did the Stokstad Report. On the one hand, it has become apparent that the region up to 200 MeV/amu is most important for the study of the evolution of various processes while, on the other hand, truly asymptotic processes are not developed until energies of many GeV per nucleon are reached. We emphasize the interest in the heaviest projectiles with energies of 40-70 MeV/amu.

B. Present Spectrum of Heavy Ion Accelerators

Figure 5 shows the performance characteristics of the major new facilities which will emerge from the presently authorized construction program. This spectrum is heavily weighted toward the lower half of the mass range, both in projectile species and in energy relative to the Coulomb barrier. Four machines will have the capability to accelerate projectiles as heavy as A=60 to at least 30 MeV/amu. In the range of projectile mass A<100 and $E \lesssim 10$ MeV/amu, five additional accelerators will be available.

> CONCLUSION 2 - A sufficient number and adequate mixture of accelerators with excellent characteristics is now available to study the energy range from the Coulomb barrier into the transition region for projectiles in the lower half of the mass table.

Only a single accelerator facility, MSU II, will provide enough energy to cover the interesting range up to 200 MeV/amu for lighter ions. This is also the only accelerator which may provide energies touching on the transition region for the heaviest beams, with intensities allowing systematic studies. Clearly MSU II will play a pre-eminent role for heavy ion physics in the U.S., in the 1980's and the 90's. It will be the only one to compare with the major new European facilities which are presently proposed or under construction. MSU II should be available for research before 1986.

> CONCLUSION 3 - Construction of MSU II should be funded as rapidly as warranted by the technical development.

While the projected capability of MSU II for lighter ions is based in large part on established experience, the intensities predicted for the heaviest ions are subject to significant uncertainties about ion source capabilities and beam dynamics.

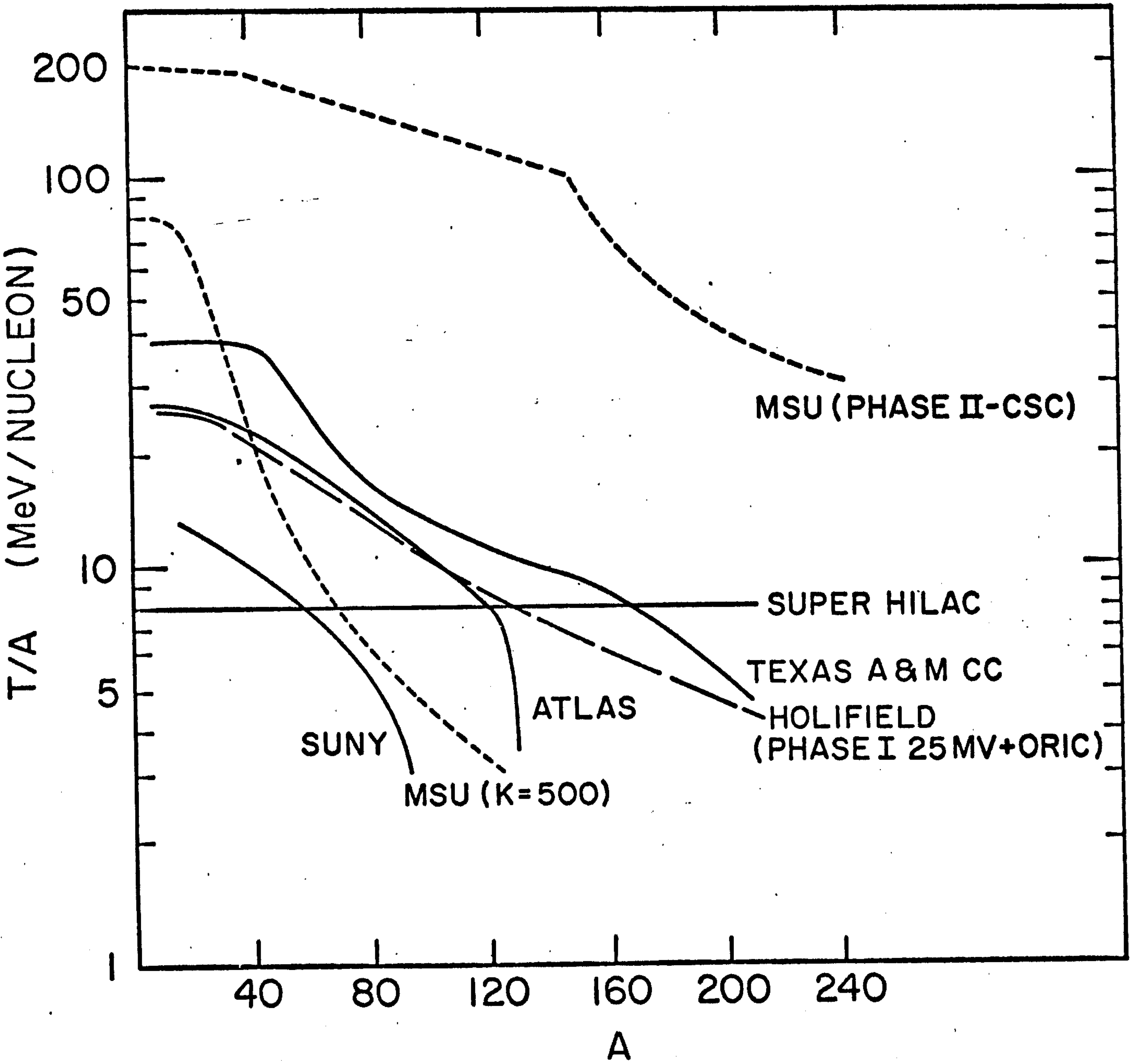

Fig. 5 Performance plot of major U.S. heavy ion facilities which are now under construction.

<u>CONCLUSION 4</u> - In view of the unique position MSU II occupies in the present plans, the extraction characteristics of ion beams near Pb from the K=500 injector cyclotron should be demonstrated as early as possible.

One could be apprehensive that phase I of the MSU project and later phase II would heavily favor at first, the demonstration and then the experimental use of lighter ion beams. It would then not be clear before the end of the decade if the present predictions for the heaviest projectiles are in fact realistic.

As are most other heavy ion accelerators MSU II is presently conceived as a single beam facility. As such, it is estimated that it can serve the needs of about 75 full-time scientists. However, the host institution itself already foresees an in-house scientific staff of 50, including students. Thus it can be predicted that this machine will be greatly oversubscribed.

The uncertainty about the heavy mass performance and the scientific load which will be placed on this facility, were major concerns of the Subcommittee.

<u>CONCLUSION 5</u> - An accelerator which can produce 40-60 MeV/amu beams of the heaviest projectile masses with low operating costs would fill a potentially significant gap in the spectrum of present heavy ion accelerators, in the range up to 1 GeV/amu considered by this subcommittee; it should have first priority for any available upgrading or construction funds.

Whether this conclusion can be made into a recommendation depends strongly on the price tag associated with such a facility, which the Subcommittee has not discussed in detail. If such a machine could be obtained at a low price, it would be a valuable complement to MSU II, especially if its operating costs would be significantly lower than those of the Superhilac.

To the extent that such a facility would create another user's facility the associated increase in operating costs could impact very negatively on other on-going programs. On the other hand, the impact may not be as large as it seems, for the following reasons: As the trend of the last two years demonstates, more and more research will be done at user's facilities. It is a privilege of the individual user to work at the facility he finds most exciting at any given time (indeed, this is almost the only advantage of the user's modes); with the new accelerators which now become operational he will have more options than before. This may introduce an element of instability into the system where older facilities become outdated and under-utilized much more rapidly than was the case before the mostly in-house research. There is evidence that this has happened in high energy physics and is happening in heavy ion physics in Europe. If this is so, any really exciting new accelerator will automatically generate its own operating costs at the expense of older and quickly under-utilized facilities.

C. University Based Research Facilities

Both the Stokstad Report and NSAC have been very concerned to preserve an experimental base at universities and this had a strong impact on recent facility recommendations.

Today, three university laboratories are upgrading to modern facilities: MSU, Texas A&M and Stony Brook; three additional upgradings at universities at FSU, Yale and Univ. of Washington have been recommended recently by NSAC. As far as the Subcommittee could determine, no other university laboratory plans to upgrade its home facility in a major way. This is undoubtably due in part to the large cost of even modest modern commercially available accelerators and the large personal commitment needed to built an accelerator from scratch. The question of University installation versus national laboratory, formerly so important, is now in essence moot.

> CONCLUSION 6 - Recommendations for future heavy ion facilities should be based on the technical and scientific merits of a given proposal with at most secondary considerations for the proposed location at University or National laboratories.

D. Operating Costs Versus Direct Research Costs

Increased costs for power and maintenance personnel require an ever increasing share of the constant funds available for research, just to operate the accelerators. The question may be asked about the balance of running any given accelerator full time at the expense of others, and operating a mix of accelerators, each part-time. Under the assumption of overall constant research funds we reached the following conclusion.

<u>CONCLUSION 7</u> - Because heavy ion science is so diverse, it is preferable to operate a mix of machines part-time, rather than a few power-intensive accelerators full-time.

Except in the case of a unique capability, such as the Bevalac, energy-intense machines should be de-emphasized relative to economic machines of the same capability.

Instrumentation is of paramount importance in heavy ion research. Our European colleagues have been able to do many pioneering experiments because of the immediate availability of funds to develop new instrumentation (for instance, GSI at Darmstadt channels funds through the main laboratory to user's groups on the basis of proposals).

<u>CONCLUSION 8</u> - Larger user's facilities should assume a responsibility to provide funds rapidly for inventive new instrumentation proposed and built by a user group.

In practical terms such funds would probably have to come out of the operating budget of the accelerator. A sound and equitable way would have to be found to distribute such funds in response to users proposals. The spirit of this recommendation is to allow the construction of inventive, even short-term, instrumentation in contrast to the large long-term equipment projects which national laboratories normally undertake. A laboratory with a designated users program should set aside a small fraction (∿5%) of the operating costs of the facilities, to be distributed by the program advisory committee to users of the facility immediately after proposal review.

E. Scientific Man-Power

The number of full time Ph.D scientists engaged in heavy ion physics in the U.S. is about 300. Based on information from the university groups dedicated to heavy ion research, there are at least 120 places available for the training of graduate students. Although some laboratories perceive a shortage of new students, this is not worse than in the physical sciences in general. More serious is the lack of good post-doctoral scientists. In a sense, this is a consequence of the broad success of the field. A high portion of recent graduates in heavy ion science have been sought by industry and applied research laboratories immediately after graduation.

There is reason to believe that many of these Ph.D would have elected to remain in basic research for a few years, before deciding on their final career. However, with industrial salaries outstripping post-doctoral saries by about a factor of two, the financial sacrifice is becoming severe. In fact, in most cases much less educated technical personnel working side by side with research associates receive significantly higher pay than the scientist.

CONCLUSION 9 - A conscious effort should be made by the laboratories to increase post-doctoral salaries.