Intermediate and High Energy Heavy-Ion Reactions

NSAC/DNP Town Meeting - Brookhaven National Laboratory
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1 Overview

The Town Meeting on "Intermediate and High Energy Heavy-Ion Reactions" was held on January 27-28, 1995 at Brookhaven National Laboratory. One hundred seventy-seven physicists attended with strong representation from both the intermediate energy (20 MeV $<$ E/A $<$ 1 GeV) and relativistic (E/A $>$ 1 GeV) heavy ion communities. The goal of the Town Meeting was to solicit the views of the heavy ion reaction community on the opportunities and needs of the field as input into the present Long Range Planning (LRP) Process for Nuclear Science (see Appendix A for more details). This involved identification of the scientific achievements of this field since the last LRP (1989), assessing the current and near-term prospects of the field by identifying the most important scientific issues to be addressed, and determination of recommendations to address these issues. At the Town Meeting speakers were invited to present overviews of the exciting physics being pursued in this field. Many physics aspects of common interest using heavy ions over the entire energy range were discussed. These included phase transitions, equations of state, effects of the nuclear medium, transport theories, nuclear dynamics, detector and analysis techniques, and the use of rare probes in heavy ion reactions. The entire first day and the early morning of the second were devoted to ten invited presentations, three proposals for major experimental equipment, three presentations on demographics of the field, twelve contributed presentations and discussion generated by these items. The agenda for the Town Meeting can be found in Appendix B at the end of this report. Two working groups, representing the two major components of the field described above, met during the late morning and early afternoon of the second day, which was followed by an open discussion of the future of the field resulting in a set of final recommendations. These are presented here and described in more detail in the text of the report:

- **The highest priority for Nuclear Science is the timely completion of RHIC construction and the operation with a complement of detectors, including the additional experimental equipment, which will ensure full realization of the scientific promise of RHIC.**

  Other high priorities:

- **The immediate upgrade of the MSU-NSCL Facility for coupled cyclotron operation is strongly recommended and is viewed as the next highest priority for construction.**

- **Pursuit of the new scientific opportunities with the recently available heavy beams at the relativistic heavy ion facilities and with the new equipment at the intermediate energy facilities is crucial for progress of the field.**

- **Strong support of theory associated with intermediate and high energy heavy ion interactions is essential for success in this field.**

2 Major Accomplishments since 1989 Long Range Plan

Most of the physics objectives anticipated in the 1989 LRP for the period up to the present were achieved including several surprises, as highlighted below.

2.1 High Energies, $E_{beam}/A > 10$ GeV

The 1989 Long Range Plan described an ambitious program to extend our quantitative knowledge of the highest energy heavy ion programs, including the determination of nuclear stopping power, the measurement of HBT correlations for pion and kaon pairs, extensive studies of flavor production systematics, and extended study of proposed Quark-Gluon Plasma (QGP) signatures. As described below, these measurements have been made, leading to both increased understanding of the underlying reaction mechanisms and to some very intriguing unanticipated results.

Recent experimental highlights:

1. Nuclear reactions producing up to 1600 pions and kaons were observed for the first time, exceeding by a factor of two the most violent, rare cosmic ray events ever recorded. This was made possible by the recent acceleration of heavy nuclear beams and accompanying measurements of Au+Au reactions at 11 A·GeV at the Brookhaven AGS and Pb+Pb reactions at 160 A·GeV at the CERN SPS.

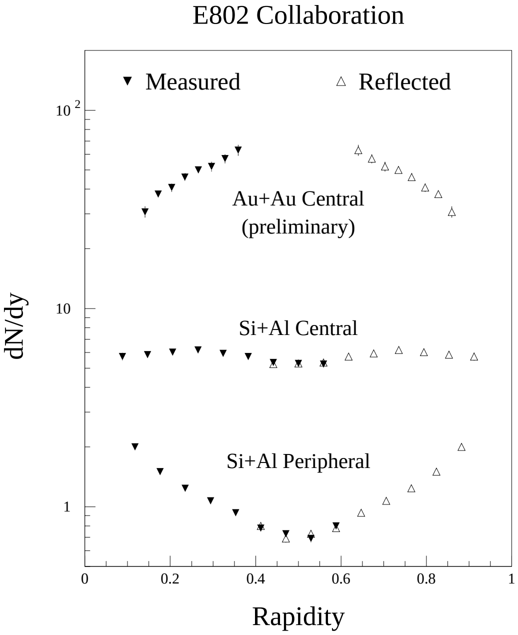

Fig. 1: Comparison of proton rapidity distributions for peripheral Si+Al and central Si+Al and Au+Au collisions at 11.6 A GeV/c (M. Gonin et al., Nucl. Phys. **A566**, 601c (1994)).

2. Considerably higher nuclear stopping power was observed in A+A collisions at AGS and SPS energies than originally predicted. At the AGS the heaviest nuclei stop each

other completely in the center of momentum frame. The increasing "pile-up" of baryons at central rapidity going from very light (peripheral Si+Al) to the heaviest systems (Au+Au) is shown in Figure 1. This is evidence for large stopping and suggests that densities as high as 10 times normal nuclear density should be reached in reactions with the heaviest beams now available at the AGS and SPS.

3. The recent discovery of collective sidewards flow in Au+Au at the AGS opens a new direction of investigation with heavy ion beams. The persistence of such collective phenomena at AGS energies, which were originally discovered at Bevalac energies, provides the opportunity of studying the equation of state at extremely high densities.

4. At the AGS baryon resonance matter has been discovered. Data show that approximately half of the nucleons are in excited states at freeze-out. A simple thermodynamic description of the system in terms of a temperature (about 130 MeV) and a baryon chemical potential is surprisingly successful, indicating that the system may be in equilibrium.

5. Strangeness production is found to be enhanced at the AGS and SPS for moderately heavy systems (using Si and S beams). Particularly surprising is the even stronger enhancement of multiply-strange baryons and antibaryons. Attempts to reproduce the strangeness yields in model calculations indicate that new physics may be required.

6. A significant suppression of J/ψ and ψ' has been observed in the form of a strong linear decrease of the yields with increasing transverse energy (energy density). This is strong evidence for the importance of successive collisions in a dense medium. The systematically stronger suppression of the Ψ', a feature not seen in p+p and p+A collisions, leaves open the exciting possibility of color screening in deconfined matter. The systematics of these effects are currently a topic of active theoretical debate.

7. In a significant extension of hadron interferometry, kaon pair correlations were measured for the first time at both the AGS and SPS. Pion pair correlations indicate a considerable amount of expansion and a freeze-out source radius which is larger than that of the projectile. The decoupling radii measured for kaons are smaller than those for pions, consistent with the differences in their mean-free paths. The observed systematic decrease of the decoupling radii with increasing transverse momentum of the pair indicates transverse expansion.

8. A significant excess, beyond expectations from p+A, of both low and intermediate mass dilepton pairs has been seen in light-ion collisions at the SPS. This source of virtual photons is currently not explained in terms of simple hadronic physics and results for the heavier beams are awaited.

9. Superconducting magnet production for RHIC started in June 1993 and is expected to be completed at the end of 1996. Industrial production is in full swing. The magnets continue to meet or exceed design specifications, and installation into the RHIC ring is underway. Construction of the two major detector systems, STAR and PHENIX, has begun. Over 700 scientific collaborators from 15 nations are involved in the experimental program and the 1999 start date is eagerly anticipated.

Highlights of theoretical work related to the above:

1. Recent large scale Lattice QCD calculations confirm that the energy and entropy density increases rapidly and the chiral condensate decreases rapidly within a rather narrow ($\sim$ 10 MeV) temperature interval around a critical phase transition temperature $T_c \approx 150$ MeV. Results of these calculations, shown in Figure 2, reveal a rich and complex structure of the phase diagram as a function of the quark flavors and masses.

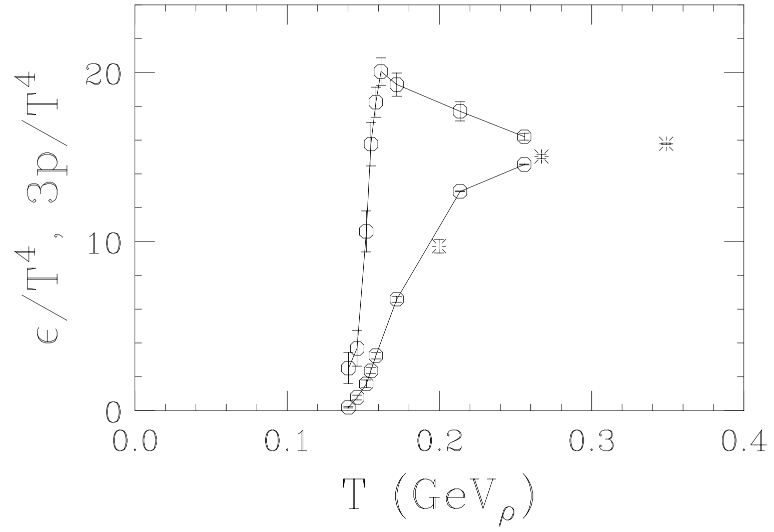

Fig. 2: Lattice QCD calculations for the energy density (upper curve) and pressure (lower curve) as function of temperature for two light quark flavors (from C. DeTar, Proceedings Lattice '94, Nucl. Phys. B Suppl., in print; hep-lat/9412010).

2. Detailed Monte Carlo transport codes have been developed that include mini-jet processes and parton cascading in addition to soft multiparticle phenomenology. Such models are now used to calculate the background in the search for new phenomena at present fixed target energies and to test detector concepts for RHIC and LHC.

3. A new signal associated with the chiral restoration transition, called the disoriented chiral condensate (DCC), was proposed. DCCs are predicted to produce dramatic signatures in pion fluctuations. New dilepton, charm, and jet signatures of the early evolution of the quark-gluon phase have also been calculated, allowing the new detector systems for RHIC to be optimized to search for these phenomena as well as a broad range of possible new signatures of dense matter.

4. A theory for the nuclear dependence of the nuclear quark and gluon structure functions has been developed that will be essential for fixing the initial conditions in parton cascade (transport) models.

5. Powerful resummation techniques were developed to regulate infrared problems in high temperature perturbative QCD. Finite kinetic transport coefficients have been calculated for the QGP phase. Classical nonabelian dynamics was found to exhibit chaotic behavior and the color conductivity of the QCD plasma was found to be surprisingly

small. Both phenomena suggest that collective color dynamics in a QCD plasma is much richer than analogous collectivity in QED plasmas.

2.2 Intermediate Energies, $E_{beam}/A < 2$ GeV

The study of nuclear multifragmentation, emphasized in the 1989 Long Range Plan as one of the major areas of interest, has advanced significantly with the advent of new 4π detection arrays. Highlights in the experimental study of multifragmentation include:

1. Observation of the onset of multifragmentation, a maximum in the fragment multiplicities for central collisions at kinetic energies per nucleon E/A=100 MeV, and a subsequent decline into vaporization with increasing energy deposition as seen in Figure 3. An unexpected failure of first generation dynamical models was observed.

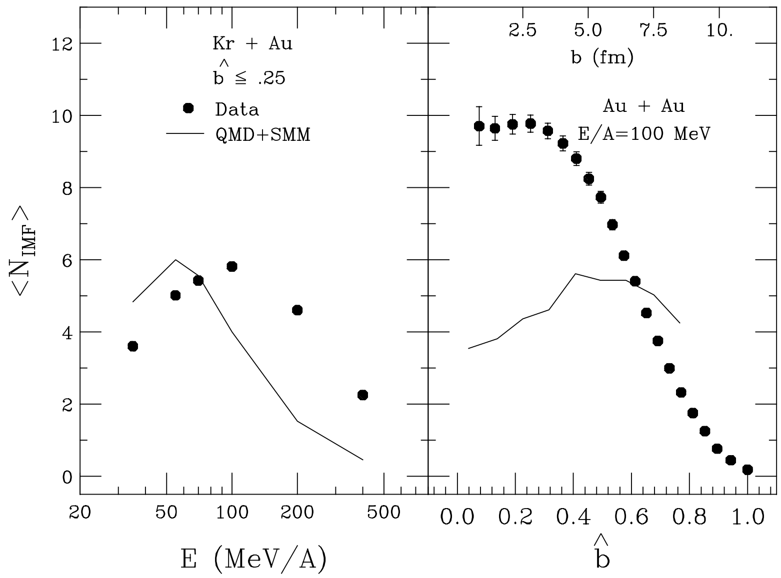

Fig. 3: Incident energy and impact parameter dependences of the mean fragment multiplicities for Kr+Au and Au+Au collisions, respectively. The solid lines are the corresponding QMD-SMM model predictions (from M.B. Tsang et al., Phys. Rev. Lett. **71**, 1502 (1993) and G.F. Peaslee et al., Phys. Rev. C **49**, R2271 (1994)).

2. Measurements of the incident energy and impact parameter dependences of fragment charge distributions.

3. Evidence for expansion in multifragmentation processes. Expansion and fragmentation at low density is a necessary condition for a liquid-gas phase transition.

4. Development of new correlation techniques to extract information about the breakup mechanism. Applications of these techniques reveal short emission timescales for multifragmentation processes.

5. Event-by-event analyses of the moments of the fragment charge distributions. Using such techniques the first extraction of critical exponents for nuclear fragmentation has been attempted.

6. Observations of the fragmentation of necklike structures in peripheral collisions and first indications for the importance of the geometrical configuration at breakup.

7. First complete event reconstruction of all charged particles and neutrons. This provides unprecedented precision in impact parameter selection and excitation energy determination.

The properties of very hot nuclei were identified as an important issue in the 1989 Long Range Plan. In the interim:

1. Nuclei near the limits of stability were isolated and their thermodynamic properties were determined.

The investigation of collective nuclear flow, the interplay between the nuclear mean field and nucleon-nucleon collisions, and the determination of the nuclear EOS were central goals of the 1989 Long Range Plan. Significant progress was achieved:

1. Observation of the disappearance of directed flow has led to the establishment of significant constraints on the medium modifications to the nucleon-nucleon elastic cross section.

2. Detection and characterization of a radially outward flow, with a velocity which increases linearly with the logarithm of the c.m. kinetic energy (shown in Figure 4).

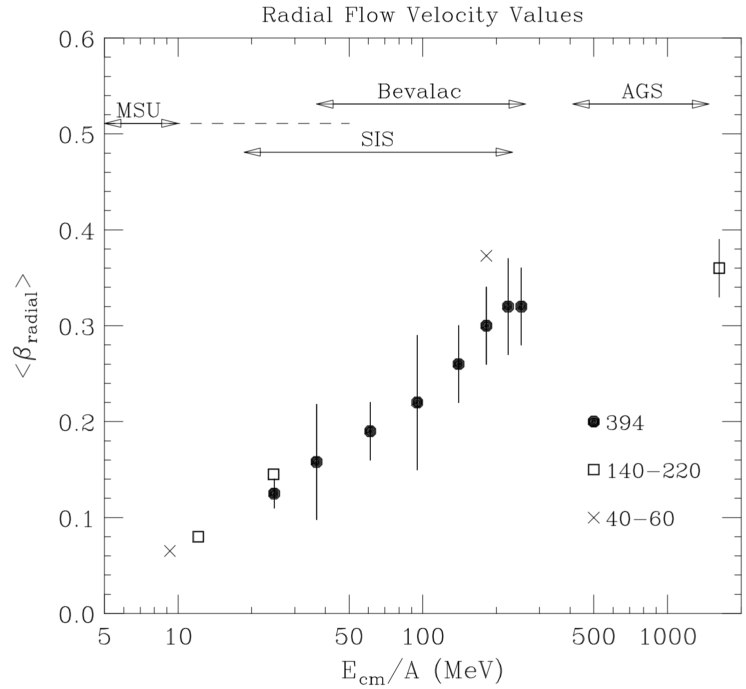

Fig. 4: Observed value for the radial flow velocity as a function of c.m. kinetic energy (compilation by M. Lisa, unpublished).

3. The prediction and detection of pionic anti-flow as a result of pion absorption and rescattering in the surrounding nuclear matter.

4. Development of techniques to determine separately the nuclear compressibility and the momentum dependence of the nuclear equation of state and the first successful applications of these techniques.
5. Experimental extraction of triple-differential cross sections and detailed comparisons of the measurements to transport theory.

The study of particle production and the propagation of short-lived particles through highly excited matter was a central goal of the 1989 Long Range Plan. Such investigations have produced the following major results.

1. Experimental determination of the incident energy dependence of subthreshold antiproton and kaon production. These observables are regarded as evidence for the existence of resonance matter in the incident energy region of 1 to 2 A-GeV.
2. First experimental investigations of di-lepton production in p+p, p+A and A+A collisions, indicating the influence of the medium on hadronic form factors.

Theoretical accomplishments relevant to the intermediate energy programs and to the goals of the 1989 Long Range Plan include the following advances in transport theory:

1. Further development and refinement of (BUU) transport models for the time evolution of the one-body phase space density, and successful application of these models to a wide variety of phenomena including energy deposition, equilibration, and collective flow. Predictions of these models now guide many present experimental investigations.
2. Theoretical techniques for the calculation of two-particle interferometry, applied first to intermediate energy collisions, now enable quantitative tests of transport theory at a variety of incident energies.
3. The development of a self-consistent transport theory for nucleons, hydrogen isotopes, and pions.
4. The incorporation of resonances into transport theory for the description of energy deposition and sub-threshold particle emission. Calculations indicate a sensitivity of the yields of subthreshold kaons to the nuclear compressibility.
5. New methods have been developed to address the problem of the origin and growth of fluctuations and multifragment decay of systems at sub-nuclear densities.
6. A first set of transport theories including explicit antisymmetrization has been developed. These new theories promise to incorporate important quantum statistical aspects at low excitation energies.

2.3 Technical Developments

In the development of the long-range plan for 1989, a strong case was made for RHIC-specific detector R&D. The very high multiplicities and particle densities expected in these nuclear collisions generate requirements unlike those encountered at ordinary hadron colliders. Additionally, the fact that many of the phenomena associated with QGP formation and detection were at much lower transverse momenta than commonly studied at colliders required special emphasis on the optimization of detectors in this regime. Accordingly, a major effort was initiated in FY90, and pursued in the years FY90 to FY95. Funding of approximately $16M was included as part of the RHIC Project for this effort.

The end result of the RHIC detector R&D has been the development of robust detector systems that form the basis of all the approved experiments at RHIC. Below a small fraction of this work is listed; a complete set of references may be found in *RHIC Detector R&D: A History and Summary*, T.J. Ludlam, RHIC Detector Note #12, rev. 1, 1994.

1. An electromagnetic calorimeter design featuring a novel "shish-kebab" readout scheme and unprecedented time-of-flight performance was developed for the PHENIX experiment.

2. A large TPC which forms the basis of the STAR detector was designed and optimized with respect to gas gain, pixel occupancy and longitudinal diffusion for the RHIC environment. Development of large-scale integrated-circuit devices will make possible the readout of hundreds of thousands of channels of electronics for these experiments.

3. New measurements of the absorption of low-energy hadrons and the penetration of low-energy muons in various materials were made. This work was essential in the design of the absorbers and identifiers for the PHENIX muon arm.

4. Precision silicon drift, pad and strip detectors for STAR, PHENIX and PHOBOS were developed.

5. Extremely precise ($\sigma < 80$ ps) time-of-flight (TOF) detectors with unique scintillator-lightpipe-PMT configurations for the PHENIX and STAR detectors were designed and tested. A sophisticated computer program was written to model the response for other geometries. The necessity for precision TOF in the STAR magnetic field led to the development of improved mesh-dynode phototubes.

The following technical accomplishments relevant to the intermediate energy programs have occurred since the 1989 Long Range Plan:

1. Development and construction of the iron dominated superconducting magnets of the NSCL beam transport and A1200 beam analysis systems.

2. Development of the NSCL superconducting ECR ion source.

3. Completion of the ISIS, Miniball, and NSCL 4π charged particle arrays and the 17 m^3 Superball and TAMU neutron multiplicity meters.

4. Design and construction of the NSCL S800 (in progress) and TAMU diproton, MARS, and MDM spectrometers.

3 Scientific Goals and Motivation

The primary physics objective of the field of heavy ion physics is exploration of the properties of matter up to the highest energy densities and baryon densities accessible in the laboratory. Particular attention has been focussed on the exploration of the phase diagram of nuclear, hadronic, and sub-hadronic matter. Theory predicts two primary phase transitions in nuclear matter. The first is the gas-liquid transition at $T \approx 10$ MeV, and the other is the deconfinement QCD transition near $T \approx 150$ MeV. This is schematically depicted by the illustration in Figure 5.

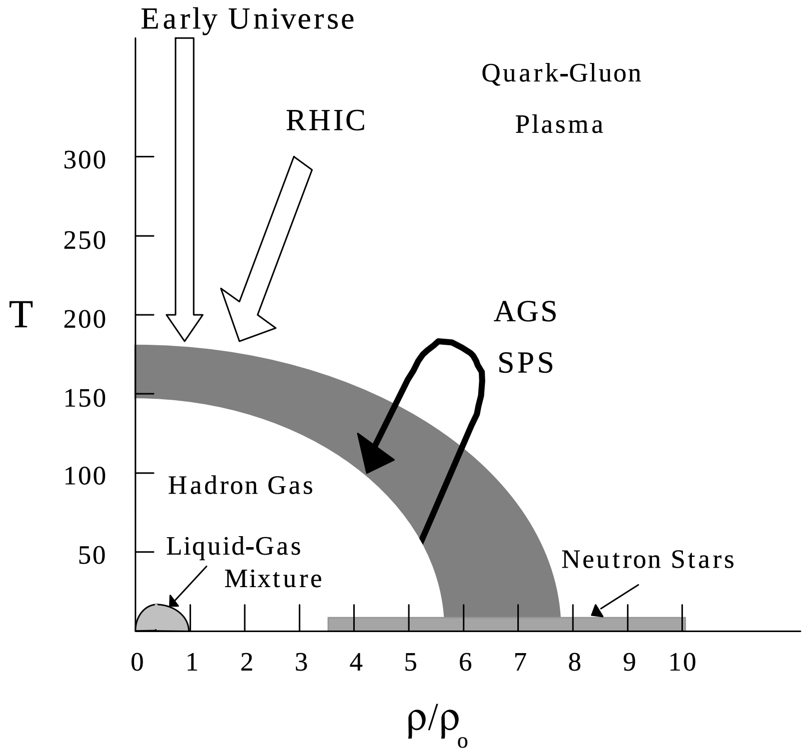

Fig. 5: The expected phases of nuclear matter, and corresponding astrophysical environments where these phases are predicted to exist or have existed are shown as a function of density and temperature (in MeV).

While other phases may exist, these two are theoretically the most compelling as they are based on modern nuclear theory and the Standard Model of strong interactions.

There are many research topics of common interest in the overall field of heavy ion reactions, from the lowest to the highest beam energies. These include: the search for phase transitions; the determination of the degree of equilibration and thermalization; the reconstruction of the space-time evolution of the system; the understanding the equation of state (of nuclear, hadronic and partonic matter); the determination of secondary particle production mechanisms; the modeling and understanding of transport processes which govern the reaction dynamics; the medium-modifications of hadronic and sub-hadronic properties such as scattering cross sections, decay widths, and masses; the isolation of collective phenomena; and the search for new phenomena. The observables utilized to accomplish this are triple differential cross sections, single particle spectra and their moments, two- and many-particle correlation functions, global and event-by-event observables (such as collective flow variables).

How these common research threads in the investigation of finite fermionic and/or bosonic quantum systems manifest themselves in detail over the various regimes of excitation energy available to present day and future accelerators is delineated below.

3.1 The Ultra-Relativistic Regime

The search for new phases and states of nuclear, hadronic, and quark-gluon matter and the understanding of the dynamical properties of strongly interacting finite systems provide the driving forces behind the initiatives utilizing present facilities at the AGS and SPS and construction of the RHIC facility. Heavy ion reactions remain the unique experimental tool to produce and diagnose matter at densities more than an order of magnitude above the density of ground state nuclei. The energy densities ($>10\,\mathrm{GeV/fm}^3$) that will be reached with RHIC are similar to those during the first few microseconds after the Big Bang and are well above the critical density ($\sim 1\,\mathrm{GeV/fm}^3$) at the critical deconfinement scale. The baryon densities reached in recent experiments at the AGS and SPS are similar to those in the dense cores of neutron stars. The also fully confirm the expectations for high energy densities at RHIC energies.

The important physics results anticipated during the next five years in high energy heavy ion physics are listed below.

At the CERN SPS and the Brookhaven AGS:

1. The properties of the high baryon density system and dynamics of the reaction process will be studied in much greater detail utilizing the new heavy beam capabilities at the SPS and AGS. The focus will be on the determination of the particle and energy densities, degree of equilibration, baryochemical potential, temperature, flow, and strangeness saturation. This information is vital to our understanding of the transient high density system that is formed in these collisions.

2. The dependence of collective flow phenomena on incident energy, atomic number, and the type of emitted particle will be mapped out at the AGS. The goal will be to distinguish between stiff baryonic matter and soft quark matter.

3. Systematics of $\pi\pi$ and K-K correlations at the AGS and SPS will provide information on the time evolution of the system. The search for a long-lived mixed phase will continue with the heavy beams.

4. Systematics of the suppression of J/Ψ and Ψ' as a function of transverse energy (energy density) for Pb+Pb reactions at the SPS is important to differentiate rescattering mechanisms from possible suppression in a QGP. The onset of suppression significantly beyond that extrapolated from p+A interactions would be indicative of the presence of color-screening in deconfined matter.

5. The excess of low and intermediate mass dilepton pairs observed in light ion collisions at the SPS will be investigated using heavy beams to establish the production mechanism.

6. A search for direct photons will be made in collisions of heavy nuclei at the SPS. If an excess of direct photons exists in collisions at these energies, they should become more prevalent for the heavier systems.

7. The new, more sensitive searches at the AGS and SPS for multi-strange hyperfragments, the H-particle and strangelets will either lead to their discovery or place stringent new limits on their production cross sections.

8. The effects of the high density medium on the mass and width of the ϕ-meson will be studied. Modifications of the properties of hadrons in the medium are predicted when chiral symmetry is restored at high densities.

9. Detailed measurements of many of the above observables will continue at the AGS and SPS for p+A reactions. These measurements are essential for distinguishing novel dynamical mechanisms in A+A reactions, such as the existence of a new phase, from simple extrapolations of p+A reactions.

Within the first year of operation at RHIC, once beams become available in 1999, we anticipate:

1. First results on the energy densities, multiplicity densities, baryon stopping, degree of equilibration, baryochemical potential, temperature, flow, and strangeness saturation (degree of equilibration at the parton level) in Au+Au collisions.

2. First "pictures" of the spacetime evolution of matter at unprecedented densities from $\pi\pi$ and K-K correlations at RHIC. Evidence for a long-lived mixed phase will be sought.

3. First tests of the effects of the high density medium and possible chiral restoration on the mass, width and decay modes of the ϕ-meson at RHIC conditions.

4. First results on the production of particles at high transverse momentum at RHIC to test the dynamics of high momentum partons in the QGP and in p+A studies constrain the degree of gluon shadowing in nuclei.

5. Measurements to study the suppression of J/Ψ and Ψ' as a function of transverse energy (energy density) for Au+Au collisions at RHIC, where the initial energy density is expected to be a factor of ten higher than that achieved in reactions at the present fixed-target facilities.

In addition to searching for new degrees of freedom in nuclear matter associated with phase transitions, a long term goal of the field is to understand the dynamics of energy deposition, stopping, formation of excitations and fluctuations, equilibration, collective flow, hadronization and the decoupling of finite strongly-interacting nuclear systems. The development of phenomenological transport models to assist in the interpretation of experimental results and the development of a quantitative quantum transport theory of hadronic and partonic systems out of equilibrium are the focus of theoretical research in this field. Measurements on the yield of direct photons and the production of low and intermediate mass dilepton pairs under the extreme conditions at RHIC will provide a penetrating view of matter at up to 100 times the energy density of ground state nuclei. This is an outstanding example of a precision probe which can be measured only in a long-term program made possible by the dedicated running uniquely available at RHIC.

3.2 The Regime of Nuclear Matter

The determination of the properties of highly excited nuclear matter at sub- or supra-normal densities is at the focus of many experimental investigations of intermediate energy heavy ion reactions.

Necessary but not sufficient conditions for a liquid-gas phase transition, such as large fragment multiplicities, short fragmentation time-scales, and the expansion and fragmentation of nuclear systems at low densities, have been observed in central and sufficiently violent peripheral collisions. Outstanding issues currently under investigation include the extraction of critical exponents, freezeout temperatures and densities, and the further determination of collective expansion velocities, and the incident energy and impact parameter dependences of multifragmentation. Significant efforts are also directed towards the search for unusual toroidal, cylindrical or bubble-like geometries that can significantly influence the fragmentation process and the subsequent extraction of statistical information.

Future issues include the essential extrapolation of multifragmentation observations towards infinite neutral matter by increasing the projectile and target masses to the largest possible values, and by varying the isospin of the system to extract Coulomb effects. These issues require the development of additional capabilities for heavy beam acceleration and radioactive beam production which can be provided by the NSCL upgrade.

A second objective of intermediate and low energy heavy ion collisions is the determination of the nuclear equation of state at moderately high densities. Recent measurements have increased significantly the information about directed transverse flow. New attention is being directed to the measurement and analysis of previously under-utilized collective radial flow and squeeze-out effects. Future directions include the comparison of weakly absorbed Λ particles to strongly absorbed pions or by examining the mass dependence of flow.

The extension of directed flow, radial flow and squeeze-out measurements through unexplored regions down to the "balance" energy ($E_{\rm bal}$), where transverse flow disappears, can provide a wealth of information about the energy dependent, in-medium nucleon-nucleon cross sections and the momentum dependence of the nuclear mean field. Further information is expected from the extension of the mass dependence of $E_{\rm bal}$ to heavier colliding systems. Both measurements require considerable new heavy beam capabilities.

The isospin dependence of the nuclear equation of state is of fundamental importance to the understanding of supernovae and the formation and ultimate stability of neutron stars. Directed transverse flow measurements involving radioactive nuclear beams (RNB's) of the proposed NSCL upgrade are feasible and can allow significant variations in system isospin for fixed system mass. In addition, measurements of nuclear compressibilities via inelastic α scattering to the monopole resonance of RNB's such as ^{132}Sn may be feasible in reverse kinematics with proposed facilities and would provide complementary information.

Determining in-medium corrections to particle production rates is the objective of many experimental investigations. Measurements at SIS of sub-threshold Kaon production, for example, have provided additional constraints upon the nuclear EOS. Very intense light and heavy beams at E/A=20-100 MeV and energetic radioactive beams from the proposed NSCL upgrade could provide intriguing future opportunities to investigate cooperative pion production mechanisms, examine pion slope anomalies, explore Coulomb effects in pion production and search for the single photon decay of the Δ resonance, etc.

Significant theoretical and experimental efforts are directed towards the investigation of quantum transport phenomena and the development of quantum transport theory. Key issues such as the dissipation and deposition of energy, the treatment of the nuclear surfaces and the growth of fluctuations leading to fragment production can be more directly addressed via collisions between very heavy projectile and target nuclei. Detailed investigations of charge transport during collisions involving radioactive ion beams offer prospects for unusual sensitivity to transport phenomena and equilibration, as well as new regimes for exploring collective γ emission. The sensitivity of isotope ratios to local isospin density fluctuations on the nuclear surface can allow explorations of the damping of such phenomena.

4 Long Range Plan

- **The highest priority for Nuclear Science is the timely completion of RHIC construction and the operation with a complement of detectors, including the additional experimental equipment, which will ensure full realization of the scientific promise of RHIC.**

The Relativistic Heavy Ion Collider (RHIC) has been the highest priority for new construction in Nuclear Science since the 1983 Long Range Plan. RHIC will be a unique, dedicated ultra-relativistic heavy-ion collider facility. It will make possible the study of ultra-relativistic heavy ion collisions at center-of-mass energies an order of magnitude higher than those available at current fixed-target facilities. RHIC will also be able to provide p+p, p+A and A+A interacting beams for comparison studies in the same set of detector systems, making it a unique facility for studying hadronic and heavy ion reactions at these energies. Construction of RHIC began at Brookhaven National Laboratory in 1991 and construction of RHIC detectors got underway in 1993. The RHIC accelerator and detectors are expected to be completed and ready for operation in early 1999.

The primary physics objective at RHIC is to create and study matter at high energy density, where a phase transition is expected from nuclear matter to a new form of matter consisting of freely-interacting quarks and gluons, known as a quark-gluon plasma (QGP). The QGP phase is believed to have existed microseconds after the beginning of the Universe and may exist now in the cores of dense stars. Another phase transition, associated with the restoration of chiral symmetry, in which the constituent quark masses fall to their "bare" or current quark mass is expected to accompany the deconfinement phase transition. The precise nature of the QGP transition is presently unknown, but under active theoretical investigation. RHIC will provide the opportunity to investigate the properties of matter at densities above that predicted for the QGP phase transition, and thus will advance our fundamental understanding of extremely dense matter.

The QGP state is expected to lead to a number of detectable signatures:

1. A relatively long-lived QGP state will result in *large system sizes and long lifetimes* which are measurable with current interferometric methods.

2. Equilibration at the parton level will result in *enhanced production of strange particles.*

3. Color screening in the QGP is expected to selectively lead to *suppression of the production of vector mesons.* The J/Ψ, Ψ' and Υ' states should be strongly suppressed, while the Υ will not be suppressed as a result of its small size.

4. *Direct radiation* from the plasma and from the mixed phase should provide information on the initial temperature, transition temperature, and the duration of the transition.

5. A disoriented chiral condensate resulting from a second order phase transition would produce *large event-by-event fluctuations in isospin* and change the *shape of the pion spectrum at low transverse momentum.*

6. The restoration of chiral symmetry can lead to *shifts in the masses and widths of light vector mesons*, such as the ρ, ω and ϕ. The electromagnetic and hadronic decays of the ω and ϕ mesons can be measured.

7. The propagation and energy loss of high momentum quarks and gluons from (mini-)jets in the plasma can lead to significant reheating and jet-quenching significantly affecting the *particle spectra at high transverse momentum.*

Timely completion of the RHIC accelerator and the RHIC detectors is imperative for effective exploitation of the science and efficient utilization of resources of the field. Completing the two large detector systems, STAR and PHENIX, at RHIC with the requested additional equipment allows a detailed, diagnostic study of the high density matter produced at RHIC and a broad search for the expected phase transitions. Without this additional equipment, searches involving many of the above signatures would be hindered or nonexistent.

Clearly the physics objectives with RHIC are multi-disciplinary, ranging from nuclear physics to astrophysics to cosmology and to particle physics. The unique capacity for major new discoveries at RHIC provides an exciting future for nuclear physics research into the next century. This is also recognized by many students and young physicists, who have joined the RHIC physics enterprise. The timely completion and operation of RHIC is therefore the most important priority of the field. This includes operation with the complement of detectors in the proposed AEE for STAR and PHENIX, as well as timely completion of the smaller experiments PHOBOS and BRAHMS. This will enable a thorough study of all aspects of the new facets and phases of matter.

- **The immediate upgrade of the MSU-NSCL Facility for coupled cyclotron operation is strongly recommended and is viewed as the next highest priority for construction.**

The proposed NSCL upgrade will nearly quadruple the energies of the heaviest stable beams at the NSCL and will provide a 10^3 increase in radioactive ion intensity, suitable for investigations of heavy ion collisions. The following important scientific issues are a few of the many that will be advanced by the upgrade:

1. Investigations of the liquid-gas phase transition
    (a) Unique high intensity heavy beams allow full exploration of the fragment observables as a function of mass to the heaviest mass and as a function of energy to the onset of vaporization. Such large systems provide the sharpest signatures of phase transitions and are an important element of the extrapolation towards infinite systems.
    (b) Unique radioactive ion beams allow the exploration of the dependence of multifragment decays upon the Coulomb interaction, further clarifying the extrapolation towards infinite nuclear matter.
2. Investigations of collective flow and the nuclear equation of state

   (a) High energy heavy beams allow the extension of the measured mass dependence of the disappearance of directed transverse flow to the heaviest systems. This will tighten the constraints upon the in-medium corrections to the nucleon-nucleon cross sections.
   (b) High energy heavy beams permit precise explorations of the onset of collective flow from the "balance energy" towards the domain of "hydrodynamical scaling" at significantly higher energies.
   (c) Unique radioactive beams permit first explorations of the isospin dependence of the EOS.

3. High intensity stable and radioactive beams permit investigations of pion emission: searches for cooperative production mechanisms, slope anomalies, Coulomb effects, photon decays of the Δ resonance, etc.

4. Reaction dynamics and quantum transport phenomena
   (a) Investigations of the incident energy and isospin dependence of fragmentation processes that proceed through toroidal, cylindrical and bubble-like breakup geometries using heavy, high energy, stable and radioactive beams.
   (b) Unique radioactive ion beams permit pioneering investigations of charge transport and equilibration. Search for collective γ emission, and local isospin density fluctuations.

- **Pursuit of the new scientific opportunities with the recently available heavy beams at the relativistic heavy ion facilities and with the new equipment at the intermediate energy facilities is crucial for progress of the field.**

1. Following the recommendations of past long-range planning, the community has invested in building a complement of experiments, now in place and capable of dealing with the unprecedented multiplicities of final state particles expected with the heaviest beams which have recently become available at the AGS and SPS. In the pre-RHIC era the highest physics priority in the field of ultra-relativistic heavy ions is to reap the benefits of these investments and to fully exploit the new physics capabilities of these upgraded facilities with existing as well as possibly new experiments. The first round of experiments established the unique feature that matter at the extremes of baryon density is created in the AGS and SPS heavy ion collisions. The important scientific issues to be addressed by use of these facilities over the next five years are described in Section 3.1 above.

   While this vigorous experimental program up to RHIC at the AGS and SPS is driven by these exceptional opportunities for physics discovery, it also has an important sociological benefit by providing young people with exciting new physics and the prerequisite training opportunity to eventually work on the much larger scale RHIC experiments.

Training the next generation of physicists to lead the field beyond the year 2000 is an important priority of this field.

2. New 4π charged particle and neutron detection arrays and new spectrometers have been constructed. These new devices, listed in section 2.3, now permit vigorous scientific investigations of the quantum transport and statistical phenomena which govern the production and disassembly of hot nuclei and of hot rarified and hot compressed nuclear matter. Support for efficient operation of the intermediate energy facilities is crucial in order to achieve the scientific objectives outlined in section 3.2, and to allow these university-based facilities to train our next generation of scientists.

   It is also foreseen that some critical investigations of multifragmentation and the liquid-gas phase transition will require the future development of a higher granularity, higher resolution and much lower threshold 4π detection system than is currently available. This new array would be designed so that it could be used in a standalone mode or in conjunction with other existing devices such as the Rochester - NSCL SUPERBALL or the new ORNL-TAMU-MSU BaF_2 array.

- **Strong support of theory associated with intermediate and high energy heavy ion interactions is essential for success in this field.**

Ever-larger amounts of data on the many-body final states produced in heavy ion collisions are collected by modern detector arrays. To extract meaningful information from these data, new observables and schemes of data reduction must be constructed, microscopic many-body simulations must be performed, and connections to the fundamental physics issues must be established. For all of these issues collaborations of theorists with the experimental community are absolutely essential.

5 Demographic Issues

The intellectual challenges and experimental opportunities provided by the study of heavy ion reactions have continued to attract researchers to this field. As an example, 340 scientists attended the Nucleus-Nucleus Collisions '94 conference at Taormina, Italy. Another indication is given by the attendance at the Quark Matter series of international conferences, which has increased by more than 10% per year, growing from 110 attendees in 1982 to 450 at the recent Quark Matter 1995 conference.

These same factors make heavy ion physics attractive to graduate students. The experimental heavy ion programs at NSCL, TAMU, the BNL AGS and the CERN SPS together produce roughly 20 Ph.D's per year. A smaller number of students, on the order of a few per year, obtain degrees in nuclear theory relevant to heavy ion collisions. There is ample evidence, both statistical and anecdotal, to indicate that the retention of these very talented young people in the field is excellent. Over the past 5-10 years, approximately 40% of the Ph.D.'s produced in heavy ion physics have taken positions in academia. Roughly one-third of those in academia occupy tenured or tenure-track faculty positions, while the remainder have research appointments. Another 35% of the graduates take similar positions in the national laboratories, while the remaining 25% are employed in industry. Those who have chosen to work in the commercial sector find employment in a great variety of fields such as aero-space, banking, bio-technology, defense, high-tech manufacturing, medical imaging, nuclear medicine and software development. As such, they represent an essential associated benefit for the nation resulting from investment in basic research that attracts the brightest and most motivated young researchers.

Two problems related to the transition from the existing programs to RHIC were identified at the town meeting. The first is to be able to continue to provide opportunities for graduate students and post-docs to develop scientific expertise in the context of fundamental research, rather than detector development alone, before the beginning of RHIC operations. It is therefore crucial that the fixed target experiments at the AGS and SPS continue to run as long as possible before the advent of science with RHIC. The scientific potential of these experiments is documented in Section 3. A second concern results from the relative lack of permanent positions, in both heavy ion theory and experiment at the national labs and universities. The growth of such appointments has not been commensurate with the overall growth of the field, and represents a serious limitation in the ultimate retention of talent developed in this field. This is a product, in part, from the perception of planning committees and administrators that nuclear physics, in general, is no longer a forefront activity. This is a misconception when applied to heavy ion physics and other highly active areas of nuclear physics. Securing additional faculty positions for heavy ion physics and other growth areas should be an important goal for the field in the immediate future.

5.1 International Cooperation

The field of heavy ion physics, as is characteristic of fundamental science, is a truly international intellectual activity. This was true of early programs in the field such as the Bevalac, and remains so to the present. Presently, 14 foreign nations carry out vigorous research programs at TAMU and NSCL. Of these, strong cooperative arrangements exist with researchers from Italy, France, Sweden, Germany and Japan. Furthermore, significant international cooperation characterizes the fixed-target programs at the CERN SPS and the BNL AGS. Foreign participation in the BNL program has been largely from Canada and Japan, with additional involvement of groups from China, Germany, India, Russia, and Sweden. Similarly, a significant contribution has been made by US-based researchers to the CERN SPS program.

The close contacts forged in these efforts, along with the complexity and cost of the required experiments, have led to extensive participation by foreign institutions in the RHIC collaborations. Of the 740 researchers already involved in RHIC experiments, nearly 50% are from outside the U.S. These scientists contribute to all phases of the experiments, including funding, detector construction and software development.

In its meeting on December 15, 1994, the CERN Council approved the construction of LHC in a staged approach, envisioning a possible start of heavy ion physics at LHC in 2004. A review in late 1997 is planned in order to monitor progress, re-examine the two-stage approach and possibly revert to the immediate construction of a full energy 14 TeV accelerator. With heavy ion physics at LHC beginning no earlier than 2004, there is an opportunity to attract more European involvement in experiments at RHIC. This would be extremely beneficial for both sides and should be vigorously pursued. The different timescales for RHIC and LHC are well-suited for this purpose. This type of European participation at RHIC could open the door for an eventual participation of nuclear physicists from the U.S. in the LHC heavy ion program. This physics opportunity should be kept in mind for future long-range planning.

On another front, the U.S. Nuclear Data Project has been working with groups from around the world to develop an up-to-date compilation of the world's data in nuclear physics. The U.S. group is planning to incorporate heavy ion reactions into the compilation and should develop this in cooperation with heavy ion physicists and with the interests of heavy ion physics in mind.

6 Cross-disciplinary relevance

6.1 Medical use of heavy ions

The lighter heavy ions (Carbon, Oxygen, Neon, Argon) are often cited as ideal particles to use for radiation treatment of malignant tumors because a) the end of range ionization peak allows the radiation dose to be accurately concentrated in a designated target volume and b) the high density of ionization along the track of individual ions makes the effect of the radiation independent of factors such as the presence or lack of oxygen in the target volume and the particular phase of cell growth. In contrast, photons, the current near-universal choice for radiation therapy are relatively poor on both of the above criteria; protons, which are now in use at a handful of centers in the world, make an important improvement in dose localization but are largely equivalent to photons in sensitivity to oxygen and in their dependence on the growth phase of the cell cycle. The major disadvantage of heavy ions, and the major challenge to the nuclear accelerator design community is that the required accelerators are very expensive – a range in tissue of about 30 cm requires nearly 500 MeV/A for Carbon and 800 MeV/A for Argon.

The use of heavy ions in radiation therapy was pioneered at the Lawrence Berkeley Laboratory using the Bevalac accelerator facility, but this program has recently been discontinued due to the high cost of operating this very old accelerator complex. A splendid new facility, the HIMAC is now coming into operation at Chiba in Japan, but its construction cost of approximately $350 million (US) will surely have to be lowered by an order of magnitude in order for facilities of this type to come into wide use. Clearly, major innovations and new breakthroughs in accelerator technology will be required to accomplish this. In the meantime this Japanese facility will be the world focus of medical research to definitively establish the benefits of heavy ions in radiation therapy.

6.2 Cluster science

The study of the nuclear liquid-gas phase transition is relevant for many-body physics beyond nuclear physics, because it allows one to study extreme finite size effects (on the order of only 10^2 constituents as compared to 10^{23} for macroscopic systems) on the character of the phase transition and observables such as latent heat or critical exponents. Since mesoscopic quantum systems (e.g. quantum dots) rapidly become more important in condensed matter physics and technology, the experience gathered with nuclear finite quantum systems may become transportable across discipline boundaries. One concrete example for this is the fragmentation of C_{60} molecules, so-called ‘buckyballs’, after bombardment with high energy (420-625 MeV) Xe ions. The observed fragmentation pattern shows striking similarities with nuclear fragmentation after bombardment with ultra-high energy protons, as shown in Figure 6.

6.3 Astrophysics

A detailed examination of the nuclear equation of state conducted in heavy ion laboratories will help answer many important questions of astrophysical relevance. Some examples are:

Core-collapse supernova

In a heavy star a series of quasi-static burning stages leads finally to a layered structure with a core of iron-like nuclei; the core then collapses to nuclear densities, and bounces, forming a shock wave that in some way expels the overlying material. The nature of the explosion depends in an important way on the size of the core and the strength of the shock wave. Electron capture and beta decay influence the core size and can be determined for the important radioactive nuclei via charge exchange in inverse kinematics at energies above 100 MeV/nucleon. The strength of the core bounce is affected by the nuclear equation of state for neutron-rich hot matter. Studies of the giant monopole resonance by inverse kinematics scattering on ^{4}He collisions of nuclei in a chain of isotopes of a single element should permit one to better isolate the asymmetry and coulomb effects. Radioactive beams will be used to obtain a sufficiently long chain. Nucleus-nucleus collisions should yield information on the temperature effects.

R-process

The rapid-neutron capture process (r-process), responsible for the synthesis of many heavy nuclei, probably takes place in a hot bubble outside supernovae cores. To understand this process requires an improved estimate of the binding energies of neutron rich nuclei, so that one can determine the r-process path; the nature of shell structure for neutron rich nuclei; and the properties of key nuclei near the waiting points. The beta-delayed neutron emission properties of these nuclei are also important. When the r-process is sufficiently understood, it will serve as a diagnostic of conditions inside supernovae.

Early stages of protoneutron stars and black hole formation

Recent studies show that quarks appear in neutron star matter after the neutrino diffusion timescale of several seconds. Catalyzed star cores containing non-leptonic negative charges such as d and s quarks lead to a larger excess of electron neutrinos than matter without such charges. Results of ongoing lattice gauge simulations and other QCD based effective field theories are of immense importance to this field. On the experimental front, a new generation of neutrino detectors is being set up to process signals from protoneutron stars and nearby supernovae.

Other areas

Other areas that will be studied include the production of ^{16}O in stellar helium burning, the production of high energy solar neutrinos, limits on hot hydrogen burning (the rp process), and synthesis of ^{6}Li, ^{7}Li by spallation reaction in the early universe.

6.4 Cosmology

Nuclear physics may play a deciding role in the fate of black hole singularities and in constraining the parameters of the standard model and particle physics. The role of the strange quark mass in the equation of state of hot and dense matter is crucial in this regard. Should

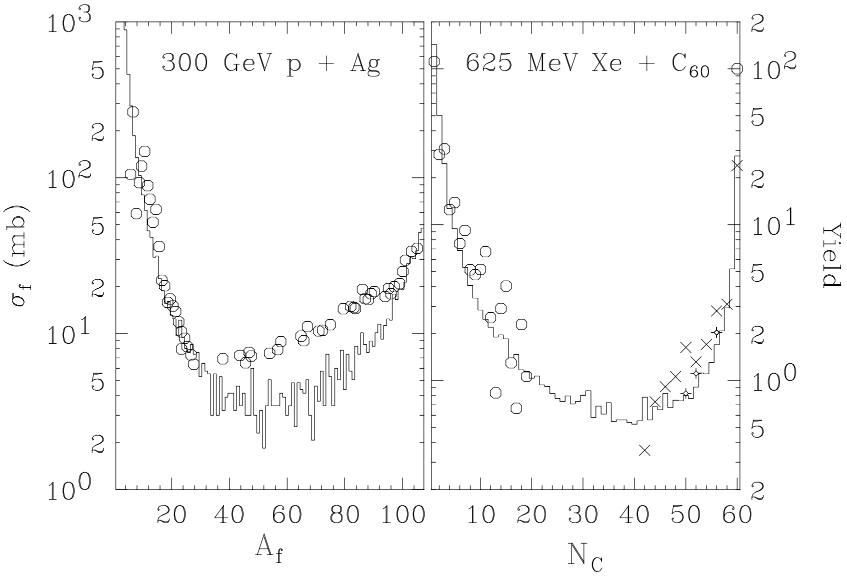

Fig. 6: Fragment size distribution from fragmentation of Ag nuclei (left, data: A. Bujak et al., Phys. Rev. C **32** 620 (1985)) and C_{60}-fullerenes (right, data: T. LeBrun et al., Phys. Rev. Lett. **72**, 3965 (1994)). Both are compared to a percolation-based phase transition model of fragmentation (histograms). And both show common features such as the characteristic U-shape, the power law fall-off for small fragment sizes, and fine structure of the mass yield due to binding energy effects.

the quark-hadron transition involve significant density inhomogeneities, light element nucleosynthesis leads to Be or B during the Big Bang epoch. Such density variations could even lead to cosmological relics such as strange quark nuggets and planetary mass black holes that could serve as candidates for cold dark matter.

6.5 Particle Physics

The quark-gluon plasma is of interest to particle physics in that it may provide important information on the origin of the masses of particles. Under normal nuclear conditions the energy densities are low, and quarks and gluons are confined in hadrons. From interactions among themselves and with their surrounding "vacuum" the quarks obtain effective masses, and chiral symmetry is broken. In contrast, in a quark-gluon plasma the energy density is high, and the quarks and gluons may interact over a large volume. In these conditions the effective masses of the quarks are reduced, and chiral symmetry should be partially or completely restored. Futhermore, the study of this truly perturbative QCD vacuum is of extreme interest.

A NSAC Instructions to the Town Meeting Convenors

In organizing the town meetings, your principal goal is clearly to bring out community views on opportunities and needs in nuclear physics. However, looking ahead to our various tasks in generating the Long Range Plan, there is a broader set of issues on which input now would be helpful. This input can help frame your white paper. Some of the key issues are:

1. Scientific achievements since 1989 Long Range Plan
    - Photos, figures and graphics?
    - Tie-in to and support of major thrusts in nuclear physics?
2. Current situation and near-term prospects
    - What are the most significant scientific issues being addressed now? What facilities/instrumentation are now in place or under development to address these?
    - What is the resource and manpower situation for effectively addressing the science?
3. Long Range Plan:
    - What are the highest priority open questions?
    - What is the likelihood of significant progress in the next decade or so?
    - Are major new capabilities needed? If so, what are the approximate capital, operating, and associated research costs? Should there be a specific project presentation at the March meeting?
    - What are the smaller scale initiatives and user group instrumentation needed for advancing the science?
    - What is the level of interest and commitment to new initiatives, particularly within a constant level of effort scenario for the field?
    - What is the attractiveness of new initiatives to young scientists?
4. Impact beyond nuclear physics:
    - What is the importance of new initiatives for the fundamental science?
    - Are there important applications of new technology associated with various programs and initiatives?
5. International involvement and opportunities:
    - What is the current level of international involvement in various areas?
    - Are new initiatives likely to generate significant collaboration?

B Program of the town meeting

- **JAN. 27**
  The program will commence at 9:00 am in the large seminar room of Bldg. 510. Discussion time following each talk is not shown in the schedule but it corresponds to about 1/3 of the time reserved for the plenary sessions.

  - Session I - Chair: G. Wozniak

    9:00 Harris - Introductory Remarks
    9:10 Gelbke - Multifragmentation
    9:55 Lacey - Tests of Transport Models
    10:25 Danielewicz - State of the Art in Transport Theories from BUU to RQMD
    11:10 Coffee Break

  - Session II - Chair: L. Schroeder

    11:30 Lisa - Collective Flow: From the Onset to the SIS
    12:00 Zhang - Collective Flow: AGS and Beyond
    12:25 Contributions / Discussion
    1:05 Lunch at the BNL cafeteria

  - Session III - Chair: P. Bond

    2:00 Cole - Strangeness
    2:30 Jacak - Fixed Target Experiments and Prospects for RHIC
    3:15 Contributions/Discussion
    3:55 Coffee Break

  - Session IV - Chair: T. Kirk

    4:25 Kirk - Introduction
    4:35 Baym - Physics Prospects for RHIC
    5:20 Braun-Munzinger - The RHIC Scientific Program
    6:05 McGaughey - The Importance of p-A Measurements at RHIC
    6:30 Contributions/Discussion
    7:00 Adjourn for Buffet Dinner at the BNL Cafeteria

- **JAN. 28**
  The second day will be dominated by the sessions for the two working groups. There will be a working group which discusses Heavy Ion reactions at SIS energies and below. The other working group will discuss Heavy Ion reactions at AGS energies and above. (Suggested topics for discussion at the Working group sessions should be forwarded to h-ions@rudolf.nscl.msu.edu)

  The program will again commence at 9:00 am.

  - Session V - Chair: G. Westfall

9:00 Demographics (Crawford, Boyd, Natowitz)

9:30 Gelbke - Coupled-Cyclotron

9:45 Hallman - STAR, Additional Detectors

10:00 Young - PHENIX, Additional Detectors

- Session VI, 2 parallel sessions

10:15 Working Groups 1, high energy, Chair: B. Zajc

10:15 Working Groups 2, intermediate energy, Chair: B. Lynch

- Session VII - Chair: J. Harris

2:30 Presentation of W.G. for SIS energies and below

3:30 Presentation of W.G. for AGS energies and above

4:30 Summary Session