Nuclear Astrophysics and Study of Nuclei Town Meeting

January 19-21, 2007

Hyatt Regency Hotel
Chicago, Illinois

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Executive Summary

In preparation of the 2007 NSAC Long Range Plan (LRP), the DNP town meeting on Nuclear Astrophysics and Structure of Nuclei was held on January 19-21, 2007, at the Hyatt Regency Hotel in Chicago, Illinois. The meeting was organized in parallel with the town meeting on neutrinos, neutrons and fundamental symmetries and the workshop on American competitiveness. Approximately 260 participants attended the town meeting from national laboratories and a wide range of universities in the United States, Canada, and, in some cases, from overseas.

The major current scientific thrusts in low energy nuclear physics and nuclear astrophysics can be organized along the following fundamental questions:

- What is the nature of the nuclear force that binds protons and neutrons into stable nuclei and rare isotopes?
- What is the origin of simple patterns in complex nuclei?
- What is the nature of neutron stars and dense nuclear matter?
- What is the origin of the elements in the cosmos?
- What are the nuclear reactions that drive stars and stellar explosions?

The last decade brought about unprecedented progress in our understanding of the nucleus and its role in the cosmos. New ideas, combined with new numerical techniques, major leaps in computing power and impressive improvements in experimental capabilities have resulted in surprising discoveries and quantitative and qualitative changes in our description of nuclear and astrophysical phenomena. This progress is reason for great optimism in the future of low-energy nuclear physics. Over the last few years a roadmap has been delineated to achieve the goal of a comprehensive and unified description of all nuclei. New experimental data are an essential ingredient of this approach as they will allow us to fully understand the nature of inter-nucleon interactions, to assess the validity of the theoretical approximations being implemented, to delineate the path towards integrating nuclear structure with nuclear reactions, and to ascertain the validity of extrapolations into new, unexplored regions of the nuclear chart. Progress in our understanding of nuclei is also essential for nuclear astrophysics, where interdisciplinary programs and initiatives have created stronger connections between astrophysics and nuclear physics than ever before. Advances in astrophysics theory and observations are constantly driving the need for new and improved nuclear data. While impressive progress has been made, particularly in experiments with stable beams, major challenges remain. For many astrophysical processes, the underlying nuclear physics is still largely unknown. This is particularly true for stellar explosions and neutron stars. While pioneering experiments with rare isotope beams have provided impressive first results, the field is still in its infancy, and is largely limited by the beam intensities available today.

Central to progress in this field is the construction of a next-generation radioactive beam facility: the Facility for Rare Isotope Beams (FRIB). FRIB will have a dramatic impact on many subfields of nuclear science, but its effect on nuclear structure and nuclear astrophysics will be extraordinary. FRIB will provide the highest intensities of rare isotopes available anywhere. Consequently, the limits of nuclear existence will be mapped, the exotic quantal systems predicted to inhabit these boundaries will be explored, and new phenomena, new types of nucleonic aggregations and key interactions will be isolated and amplified. FRIB will also provide the data needed to answer the fundamental questions posed by advances in theoretical astrophysics and astronomical observations. A unique opportunity exists to produce and study the nuclei that govern stellar explosions, are the progenitors of the stable nuclei found in the Universe today, and are ubiquitous in the crust of neutron stars. With FRIB the degree of asymmetry in heavy-ion collisions will be increased and constraints on the equation of state required for the understanding of neutron stars will be obtained.

Since the 2002 LRP, and specifically its second recommendation identifying the Rare Isotope Accelerator (RIA) as the major priority for new construction, the low-energy community has focused its efforts in theory and experiment towards this long-term goal. It has enthusiastically subscribed to the vision that such a facility will provide unprecedented scientific opportunities by opening new vistas in nuclear structure, dynamics, and astrophysics, while delivering in large quantities the isotopes required for testing the fundamental laws of nature and for numerous societal applications. During the last five years, the scientific case for the facility has grown even stronger, culminating in the recent endorsement by the National Academies of Sciences in the RISAC report.

FRIB, the facility concept compatible with projected funding levels that is currently under consideration, is based on a superconducting heavy ion driver linac capable of producing 400 kW beams of all elements from uranium (200 MeV/nucleon) to protons (580 MeV). The retention of technical capabilities in the reduced-cost facility is largely due to the significant progress made in the past few years through the RIA R&D program. As a result, FRIB will provide the community with the opportunity of a world class research program with stopped, re-accelerated and fast rare isotopes. In the global context, the FRIB capabilities are truly outstanding: the reaccelerated beams based on the heavy ion driver and gas catcher concepts are not included in any current or planned facility worldwide. In addition, the 400-kW beams from the driver support production of the highest intensity rare isotope beams. For stopped and reaccelerated beams, the capabilities of FRIB are quite similar to those projected for RIA for over 80% of the isotopes produced. The rates for fast beams are still at least an order of magnitude higher than RIKEN's RIBF and GSI's FAIR facilities, preserving the capability of exploring the regions farthest from stability.

With FRIB as the long term goal, the community has identified a roadmap for the next decade that will ensure the continued intellectual vitality of the field: forefront research at existing U.S. and international facilities needs to be strengthened in order to stimulate new discoveries, train new people and develop new concepts, new detectors and new accelerator technologies. Appropriate funding for operations and near-term upgrades of existing rare isotope and stable beam research capabilities at national laboratory and university facilities represents the path forward. In combination with specific capabilities offered by the international facilities coming on-line in the next decade, it will provide the community with the ability to explore further the major scientific issues mentioned above. At present, the effective utilization of the national user facilities remains a concern as is the adequate support of the stable beam facilities devoted to nuclear astrophysics.

The strengthening of operations and the facility upgrades should go hand in hand with the continued development of the state-of-the-art instrumentation required to best address the science. This approach also guarantees that a suite of first rate detectors will be available for first experimentation with FRIB. In this area, the timely and cost effective completion of the GRETA tracking detector was identified as a priority. With a spectrometer of this unprecedented sensitivity it will be possible, for example, to document alterations in shell structure in neutron-rich systems, to investigate the structural properties of the heaviest elements, and to explore the exotic shapes predicted to occur at the highest angular momenta. The cost effective and timely completion of GRETA requires the start of construction to take place at the completion of the GRETINA array.

For the approach outlined above to be successful, adequate support for nuclear theory is essential. The nuclear structure and nuclear astrophysics community shares the concerns about insufficient funding expressed in the 2003 NSAC Theory subcommittee report and subscribes to the overall increase in funding for nuclear theory that this report recommended. As stated above, substantial progress can be made during the next decade towards achieving a comprehensive and unified microscopic description of the structure of all nuclei and their reactions from the basic interactions (rooted in QCD) between the constituent nucleons. Further exploration of nuclear forces and currents, effective interactions, and techniques to solve the nuclear many-body problem in the regime of weak binding is a priority. While the number of creative, young scientists, who are fast becoming leaders in the revitalization of nuclear theory, has increased, the present level of manpower is insufficient to carry out the current program, let alone to take advantage of the new opportunities.

The need for strong support of education and outreach activities was a prevalent concern throughout the town meeting. Education in low-energy nuclear science is essential not only for addressing the scientific challenges, but also for societal applications and there is a real danger that without adequate support today the highly skilled workforce required in the next decade will not be available. The critical need to maintain, if not expand, the number of talented experts in nuclear science can only be met by having forefront research opportunities for undergraduate and graduate students as they are offered by the cutting edge low-energy accelerator facilities currently operating. Furthermore, the prospective of the construction of FRIB will attract the most talented students into the field.

It is hoped that the present white paper will communicate the sense of great anticipation and enthusiasm that came out of the town meeting. Over the last decade, the nuclear structure and astrophysics community has increasingly organized itself in order to take a coherent approach to resolving the challenges it faces. As a result, there is a high level of optimism in this community in view of the unprecedented opportunities for substantial progress.

The town meeting culminated in the formulation of the following statement of recommendations for the LRP planning committee:

1. **The physics of the nucleus is a fundamental component of modern science, and understanding exotic nuclei is essential to address this physics. The study of rare isotopes is therefore compelling not only for the breakthroughs it will allow in understanding nuclei and their role in the cosmos, but also for the many cross-discipline contributions it will enable in basic sciences, national security, and many societal applications. To pursue this science, to educate the next generations of nuclear scientists and to maintain its cutting edge in this field, it is imperative that the U.S. initiate a major investment into a more powerful rare isotope production facility as early as possible. We therefore recommend that:**

    - ***The highest priority in low-energy nuclear physics be the construction of a heavy-ion linac based rare isotope facility, including the capabilities for stopped, re-accelerated and in-flight beams to realize the scientific potential defined by the community and endorsed by the National Academies of Sciences in their recent RISAC report.***

2. **In support of this science goal, we must continue forefront research at existing facilities to make new discoveries, train new people and develop new detector and accelerator technologies. Hence, we also recommend that:**

    - ***Appropriate funds for operations and near-term upgrades of existing rare isotope and stable beam research capabilities at ANL, NSCL, ORNL, and other national and university facilities be supported together with a strong theory program and interdisciplinary initiatives. In particular, it is critical that funding be increased immediately to allow the effective utilization of the U.S. national user facilities;***

    - ***Construction of the GRETA array begin immediately upon the successful completion of the GRETINA array;***

    - ***Support for nuclear theory to address key questions in nuclear structure, nuclear reactions, and nuclear astrophysics be strongly increased to nurture young scientists in this critical area of research in concert with an overall funding increase for nuclear theory as recommended in the 2003 NSAC Theory subcommittee report.***

3. **Education and outreach are key components of any vision of the future of the field of nuclear science. We therefore fully endorse the recommendations of the education white paper.**

White Paper

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The objective of low-energy nuclear physics is to understand the nature of nucleonic matter by exploring the many-body degrees of freedom of the nuclear system and their dependence on the number of protons and neutrons, excitation energy and angular momentum. The ultimate goal of this field is to understand the nature of the nuclear force and its manifestation in the properties of nuclei and their reactions. This will require the development of a microscopic theory of all nuclei and their low-energy reactions from the basic interactions between the constituent nucleons. Understanding the fundamental many-body problem of nuclei requires a close interplay between theory and experiment.

The objective of nuclear astrophysics is to understand the nuclear processes that are responsible for the origin of the elements in the cosmos, that drive stars and stellar explosions, and that define the nature and evolution of neutron stars. One of the ultimate goals is to understand the chemical history of the Galaxy so that nuclear processes can serve as probes to address other fundamental questions, such as the formation history of the Galaxy, mixing processes in stars, and the nature of matter at extreme densities. Advances in nuclear astrophysics require a close interplay between nuclear experiment, nuclear theory, theoretical astrophysics, and observations. This also includes neutrino physics, which is covered by another white paper from a separate, jointly held town meeting.

The major scientific thrusts in this area can be organized along the following broad questions:

- What is the nature of the nuclear force that binds protons and neutrons into stable nuclei and rare isotopes?
- What is the origin of simple patterns in complex nuclei?
- What is the nature of neutron stars and dense nuclear matter?
- What is the origin of the elements in the cosmos?
- What are the nuclear reactions that drive stars and stellar explosions?

The current scientific questions that fall under these five broad themes are discussed more comprehensively and in much more detail in the summaries of the various working groups that are part of this document. Here, we only very briefly discuss some of the questions to be addressed in the next decade and we refer the reader to the working group summaries for a more complete and detailed discussion.

The nucleus is a truly unique, self-bound, open quantum many-body system, made out of two types of fermions where intricate forces, which have yet to be fully determined, produce a fascinating variety of behaviors. While much progress has been made in understanding various nuclear properties, a fully microscopic description of the nucleus is still lacking. As implied by the first main question, our present understanding of nuclear binding is not sufficient for us to determine the limits of the nuclear landscape. As a result, we are unable also to predict with suitable accuracy the properties of the exotic, short-lived nuclei that are located along major nucleosynthesis paths such as the r- and rp-processes. In the same way, our present understanding of the interaction between nuclear species is insufficient to describe with suitable accuracy the reactions that occur in the cataclysmic events of the cosmos.

What is the nature of the nuclear force that binds protons and neutrons into stable nuclei and rare isotopes?

An alternative and complementary way to present this question is as follows: How are nuclei assembled from their fundamental building blocks and interactions? The last decade brought about unprecedented progress in our understanding of the nucleus: new ideas, combined with new numerical techniques, major leaps in computing power and impressive improvements in experimental capabilities have brought quantitative and qualitative changes to nuclear modeling. This progress is reason for optimism that some of the fundamental questions that nuclear science seeks to answer can finally be addressed: How do two-body and three-body (and possible higher order) nuclear interactions emerge from QCD, and how do they impact both the structure and reaction properties of nuclei? What are the limits of nuclear binding? How do nucleonic shells evolve with neutron and proton numbers? How does weak binding affect nuclear properties? What is the equation of state of nuclear matter made of nucleons? These questions are of interdisciplinary character: they connect the nucleus to other complex systems and to the cosmos.

It is only over the last few years that a roadmap has been delineated to achieve the goal of a comprehensive and unified description of all nuclei. What has been proposed is a path that bridges light nuclei, where properties can be calculated with increasing success in terms of protons and neutrons interacting via two- and three-body bare forces, with medium mass nuclei, the domain of configuration interactions, and heavy nuclei where density functional theory is the tool of choice. In other words, while there is no “one size fits all” theory for nuclei, the methodology is to link all approaches to the underlying physics arising from the strong interaction between protons and neutrons and to connect the latter with QCD. Many connections will be provided by techniques of Effective Field Theory and the Renormalization group that have revolutionized the way of thinking about nuclear structure. New experimental data are crucial to fully understand the nature of the inter-nucleon interactions, to assess the validity of the theoretical approximations to be implemented, to delineate the path towards integrating nuclear structure and nuclear reactions, and to ascertain the validity of extrapolations into new regions of the nuclear chart.

These data are especially needed for nuclei far from stability where many of the known nuclear properties are expected to change significantly. Recent experimental results provide intriguing indications of these changes: many are described in the summaries of the working groups later in this report. Just a few examples are given here. For decades the cornerstone of nuclear structure has been the concept of single-particle motion in a well-defined potential leading to shell structure and magic numbers. We have now learned that the magic numbers are not immutable: they appear to depend on the neutron-to-proton asymmetry and the binding energy. A number of recent measurements indicate that the magic numbers 8, 20, and 28 no longer apply to neutron-rich nuclei such as $^{12}Be_8$, $^{32}Mg_{20}$, or $^{44}S_{28}$. Additional stability occurs for near drip-line oxygen nuclei with neutron numbers 14 and 16, as well as for N = 32 neutron-rich Ca, Ti, and Cr isotopes. Recent studies of knockout reactions on radioactive species indicate that spectroscopic factors are reduced when the transferred nucleon is a minority species (e.g neutrons in a proton-rich nucleus) and enhanced when the transferred nucleon is a majority species (e.g neutron in a neutron-rich nucleus). The reduction or enhancement is beyond that predicted by large-basis shell model calculations. Similar conclusions are obtained from elastic scattering analyses that model the correlations using the dispersive relations required by causality. First reactions between neutron rich projectiles and targets in the vicinity of the Coulomb barrier provide indications of an as yet not understood isospin dependence of the fusion barriers. Direct evidence for neutron skins (electric dipole pygmy modes) has been found in neutron-rich systems. For stable nuclei, electron scattering experiments have provided tantalizing evidence for deuteron-correlations. These manifest themselves through the dominance of correlated neutron-proton pairs over proton-proton pairs at intermediate nucleonic distances.

What is the origin of simple patterns in complex nuclei?

One of the most remarkable features of atomic nuclei is that their spectra often exhibit an astonishing degree of regularity; this indicates the presence of many-body symmetries. It is remarkable that a collection of several hundred nucleons, interacting via a strong, and complicated force that has two-, and, at least, three-body components, shows such regular, collective behaviors. At present, most theoretical descriptions for these symmetries are fairly schematic. Since they lack a firm microscopic foundation, they generally fail to have robust predictive power, and thus are more useful to categorize symmetries. Understanding just how these symmetries arise and how to utilize them in our studies of nuclei are questions of profound interest both from a theoretical and experimental perspective.

One example of recent progress relates to the study of phase transitions associated with the nuclear shape. In some regions of the nuclear chart, the nuclear shape changes with the addition of one or two nucleons and the underlying spectra can be explained well in terms of critical-point symmetries. An intriguing feature of very proton-neutron asymmetric nuclei is the prediction that protons and neutrons distributions will have rather different shape deformations. Hence, unexpected types of collective excitations, such as oscillations of the two deformed systems with respect to one another, may give rise to collective states of low excitation energy and also to new types of band structures at high angular momentum. Moreover, at the drip lines, in the region occupied by nuclei with halos or skins, a more fundamental question arises. The concept of a nuclear shape implies a well- defined surface. Such a geometric picture may break down in the limit of a diffuse surface resulting from weak binding. For example, the shape of a neutron halo may be determined by the spatial distribution of the valence nucleons, independently of the shape of the core, and this situation may give rise to new types of collectivity. The probing of such key concepts requires access to specific nuclei whose structure allows the amplification and isolation of those components of the effective interaction and those features of nucleonic correlations that depend most sensitively on the neutron-to-proton ratio.

Our concept of pairing phases in nuclei is undergoing a revolution as a result of insights from light nuclei with large neutron excess. A challenge for the future is the description of novel pairing modes in neutron-rich nuclei (strongly influenced by a neutron-to-proton imbalance and weak binding) as well as deuteron-like pairing in proton-rich nuclei that is carried by proton-neutron pairs having their spins aligned in the same direction. Progress on these issues again requires the availability of beams of exotic nuclei.

What is the nature of neutron stars and the dense nuclear matter?

Neutron stars are among the most fascinating astrophysical objects: their structure and evolution are largely determined by nuclear physics, and they play a central role in many astrophysical explosions such as supernovae, X-ray bursts, and possibly gamma-ray bursts. The basic properties of neutron stars such as their mass, radius, and cooling behavior are determined by the nuclear equation of state, which remains largely unknown. For accreting neutron stars, reaction rates with exotic isotopes on the surface and in the crust determine other key observables such as X-ray bursts and superbursts (see stellar explosions below).

The key questions in this area are: What is the maximum mass of a neutron star? What is the mass-radius relationship? How do neutron stars cool? What is the composition of the interior? What is the physical origin of transient phenomena? Major progress has been made since the last long range plan. Observationally, neutron stars with masses significantly beyond 1.4 solar masses have finally been discovered. Space-based X-ray observatories have provided reliable measurements of neutron star radii, and mass measurements of binary pulsars have begun to constrain the nuclear equation of state. Seismic modes may have been observed that would constrain the neutron star crust thickness. New observations of the cooling of transiently accreting neutron stars provide first hints for the existence of non-standard cooling processes, such as a direct Urca process, in the neutron star interior.

One critical nuclear physics ingredient for modeling neutron stars is the equation of state for cold dense nuclear matter. Therefore, neutron star observations do also address fundamental questions in nuclear physics. An important issue is the existence of exotic phases such as quark or Bose condensates at the highest densities reached in the centers of neutron stars. The existence of such phases and their nature directly impact neutron star properties such as the cooling behavior. A recent accomplishment in nuclear theory is the realization that the ground state of cold baryonic matter at extreme densities is a color superconductor in the color-flavor-locked phase. Heavy-ion collisions have, for the first time, given quantitative constraints on the equation of state of nuclear matter. A particularly important aspect in this area is the density dependence of the symmetry energy, and first constraints have recently been extracted from suitable observables in heavy-ion collisions of isospin-asymmetric nuclei.

The goal for the next long range planning period is to achieve dramatic improvements in our knowledge of the equation of state and the nature of neutron stars through both terrestrial experiments and neutron star observations. This will require a next-generation rare isotope facility to increase the degree of asymmetry in heavy-ion collisions. Electron scattering experiments at JLab will yield precision measurements of neutron skins, which will provide additional constraints on the density dependence of the symmetry energy. X-ray observatories with increased sensitivities will be needed to measure neutron star properties with higher precision. Timing measurements of binary pulsars have the potential to improve constraints on the fractional moment of inertia in the crust. In addition, advanced gravitational wave detectors have the potential of detecting signals from neutron star binary mergers that would further constrain the radius and composition of neutron stars.

What is the origin of the elements in the cosmos?

Since the last long range plan, the observation of elemental abundances in the Galaxy has seen transformational progress. Large scale surveys together with follow-up studies at the largest earth and space based telescopes have hugely increased the sample of metal poor stars with well known composition, in this way mapping the chemical enrichment history of the Galaxy in unprecedented detail. Perhaps most important for this field are the signatures of heavy element production that reveal with unprecedented clarity the operation of the rapid neutron capture process (r-process) in the early Galaxy. This process is thought to have produced about half of the elements beyond iron in the Universe; yet, its site and precise nature are still unknown. Indeed, the question of the origin of the heavy elements made in the r-process has been identified as a key question in nuclear astrophysics in many reports, including the NRC study "Connecting Quarks with the Cosmos". Recent observations point to an r-process mechanism producing a rather stable abundance pattern from event to event, but also reveal some variations. In particular, it is now clear that an additional, new process of largely unknown nature contributes to the abundance of lighter "r-process" elements beyond iron.

The necessity to compare the new observational data quantitatively with models and to disentangle different processes has dramatically reinforced the need to understand the nuclear physics of the r-process. Major experimental advances have occurred since the last long range plan with the investigation of r-process waiting point nuclei at the N=50 and N=82 closed shells, including the β-decay of ^{78}Ni and ^{130}Cd as well as neutron transfer studies near ^{132}Sn. Nevertheless, experimental studies of r-process nuclei are still in their infancy, and the vast majority of the data required to interpret the new observations have to wait for the next generation FRIB facility, which is, therefore, of critical importance for this field. Advances in nuclear theory that would lead to a reliable description of the extremely neutron rich, heavy nuclei in the r-process are also essential as some r-process nuclei may well remain out of reach to experiments.

While new observations continue to drive the field forward in surprising ways, advances in nucleosynthesis modeling have also led to major changes in our views on how elements are produced in the cosmos. An example is the theoretical prediction of yet another entirely new nucleosynthesis process, the νp-process, thought to occur in the early phases of a neutrino driven wind in supernova explosions and possibly responsible for the synthesis of proton rich isotopes solving the long standing problem of the origin of the neutron deficient Mo and Ru isotopes in nature.

It is of critical importance that the pace of progress in nuclear physics experiments and theory be comparable to that achieved in astrophysics theory and observations. Without an understanding of the underlying nuclear physics, the ultimate goal to understand the chemical history of the Galaxy and its various components cannot be achieved. Once the modeling of nucleosynthesis processes is on a solid nuclear physics footing, these can then be used as powerful probes to address other fundamental questions related to their environment. It is a major accomplishment for nuclear astrophysics that, to some extent, this has already been achieved for a few processes involving primarily nuclei closer to stability. Examples include big bang nucleosynthesis, which is used to constrain the baryon content of the universe, the pp-chain in the sun, which is used to constrain neutrino properties, and the s-process, which begins to be used to learn about mixing processes inside stars. The goal for the coming long range plan and beyond is to achieve similar successes for the processes involving mainly unstable nuclei, such as the r-process, the p-process, and the rp-process. With the utilization and further developments of existing rare isotope facilities, and the next generation rare isotope beam facility FRIB, significant steps towards this goal are within reach for the first time.

What are the nuclear reactions that power stars and drive stellar explosions?

Nuclear reactions are the engine of stars, and stellar explosions such as X-ray bursts and thermonuclear supernovae. A major accomplishment since the last long range plan is the precision measurements of reaction rates in the pp-chain and the CNO cycles powering most stars, including the sun. New measurements of the $^{14}N(p,\gamma)^{15}O$ reaction show its rate to be about a factor of 2 lower than previously thought. This increases the derived ages for globular clusters, and related limits for the age of the Galaxy, by about a billion years. Progress has also been made with one of the key reactions of the field, the $^{12}C(\alpha,\gamma)$ reaction that has a major impact on stellar evolution, although reducing the uncertainty further to the level required by stellar models remains a major challenge.

Although progress has been made in multi-dimensional modeling of the hydrodynamics and the neutrino transport of core-collapse supernovae, a detailed understanding of the explosion mechanism remains an important astrophysical problem. These events are initiated by gravity, but nuclear physics plays an essential part in the dynamics of the collapse and in the nature of the core bounce. Electron capture rates on stable and unstable nuclei are a key ingredient for modeling supernovae of all types. Recent advances in nuclear theory have fundamentally changed our view of the role of electron captures on nuclei in core collapse supernovae and have significantly expanded the range of nuclei that participate in such processes, leading to major changes in the astrophysical models. Experimental data testing these new theoretical predictions are required. While great progress has been made on stable nuclei, experimental approaches to measure charge exchange reaction rates on unstable nuclei are in their infancy. A new rare isotope beam facility such as FRIB will be required to perform the necessary systematic measurements across all relevant isotopes.

Classical novae and X-ray bursts are thermonuclear explosions on the surface of white dwarfs and neutron stars, respectively. Key questions about novae concern their contribution to nucleosynthesis, including radioactive isotopes, mixing mechanisms, and how system parameters such as the mass of the white dwarf can be constrained by new observations of the ejecta composition. X-ray bursts are the most frequent thermonuclear explosions in the Universe and major advances in X-ray astronomy have led to the discovery of a range of new exciting phenomena such as superbursts, millisecond oscillations, and indications of absorption lines. While these observations have triggered significant progress in theory, major questions remain.

To address the open questions related to novae and X-ray bursts and to interpret the multitude of observations, an accurate understanding of the underlying nuclear reaction rates is required. These concern mostly neutron deficient, unstable nuclei that burn hydrogen and helium at extreme temperatures and densities. Pioneering measurements of reaction rates and masses have been carried out with the present generation of stable beam and rare isotope beam facilities and a number of new direct and indirect techniques have been developed. They provide constraints on a number of critical rates. For the lower temperature burning in novae this has led to an impressive reduction in the nuclear physics uncertainty in the models. On the other hand, in the case of X-ray bursts, the vast majority of reaction rates is still based predominantly on theory and the associated uncertainties are large. While existing rare isotope and stable beam facilities will make progress in this direction in the near future, the wide range of high intensity rare isotope beams offered by FRIB will be essential to put the rp-process in X-ray bursts on solid nuclear physics grounds.

The Major Opportunity for our Field: The Facility for Rare Isotope Beams (FRIB)

The five main questions discussed briefly above through illustrations taken from the summaries of the working groups provide a picture of the aspirations of a community that has been preparing itself over the last decade for a major step forward with the development of a next-generation facility for the production and acceleration of rare isotopes. This facility is currently named the Facility for Rare Isotope Beams (FRIB). The science case for such a facility has been documented and endorsed by NSAC seven times in the last decade. Most recently, it has also received a strong endorsement by the National Academies of Sciences in their RISAC report. The opportunities are numerous and advances in all aspects of the science depend on critical experiments that can be uniquely performed with specific isotopes that are not available at the present time in sufficient quantities. The science can be placed in four general categories. FRIB will enable us to:

- Develop an overarching picture of the nature of nucleonic matter: FRIB will define and map the limits of nuclear existence, make possible the exploration of the exotic quantal systems that inhabit these boundaries, and isolate, amplify or reveal new phenomena, new types of aggregations, and key interactions in ways that stable beams cannot. FRIB will provide new foundations for the description of all nuclei as it offers the promise to guide the development of a unified theory of the nucleus in which both the familiar properties and excitation modes of the nuclei at or near stability and the exotic structures far from stability may be encompassed in a single theoretical framework.

- Understand the origin of the elements and the nuclear energy sources in stellar explosions: FRIB will provide key data, such as masses, lifetimes, and reaction rates needed for a quantitative understanding of important nucleosynthesis processes such as the r- and rp-processes. Hence, it will provide the nuclear physics input required to address one of the key science questions in the NRC report "Connecting quarks to the cosmos", i.e., “How were the heavy elements from iron to uranium made?”

- Test fundamental symmetries and search for physics beyond the Standard Model: FRIB will produce specific isotopes with nuclear amplifications of the physics signals and such high yields that it will provide new opportunities for high-precision measurements advancing the study of CP and P violation, providing new experimental tests of the unitarity of the CKM matrix, and probing for new physics beyond the V-A description of the weak interaction.

- Provide isotopes for applications: FRIB will provide large quantities of new isotopes with unique properties that can be harvested for applications in human health, environmental and geosciences, nuclear energy, food and agriculture, material sciences, chemistry and biology, etc. There is also considerable interest in the area of national security, specifically in the areas of stockpile stewardship, homeland security and non-proliferation of nuclear materials, and diagnostics for high energy density physics facilities.

FRIB is based on a superconducting heavy ion driver linac capable of producing 400 kW beams (the same beam power as in the original RIA proposal) of all elements from uranium (200 MeV/nucleon) to protons (580 MeV). The beams are delivered to a high power target, with the resulting rare isotopes being collected in a two-stage fragment separator and delivered to a gas-catcher. The extracted ions are purified by an isobar separator and then either used directly in stopped ion experiments or injected into a charge breeder to be accelerated to energies required for nuclear astrophysics and nuclear structure research. After the separator the rare isotopes can also be delivered directly to experimental instruments for research at ~150-200 MeV/nucleon. The production of rare isotopes via spallation or fission of heavy targets with high power light ion beams in an ISOL facility for extraction and delivery to the stopped and reaccelerated beam research areas can also be implemented.

In the global context the FRIB capabilities are truly outstanding: reaccelerated beams based on the heavy ion driver and gas catcher concepts are not included in any current or planned facility worldwide. Furthermore, 400-kW heavy and light ion beams from the driver support production of the highest intensity rare isotope beams for both in-flight and ISOL-based research available anywhere. For stopped and reaccelerated beams, the capabilities of FRIB are similar to those projected for RIA for over 80% of the isotopes produced. The rates for fast beams are at least an order of magnitude higher than RIKEN's RIBF and GSI's FAIR facilities. The retention of technical capabilities in the reduced-cost facility is largely due to the significant progress made in the past few years through the RIA R&D program.

However, FRIB in the baseline designs currently under discussion sacrifices significant capabilities to reduce the cost to less than half that of RIA. These include: 1) an approximately order of magnitude decrease in performance for those isotopes that are most efficiently produced by in-flight fission of uranium beams, 2) limited multi-user capability, 3) reduced intensities of rare isotope beams for masses less than 70 at astrophysics energies due to the elimination of the 1+ injector, 4) smaller experimental areas, 5) little new experimental equipment included in the facility costs, and 6) reduced purity of heavier in-flight beams due to the broader charge state distributions at the reduced energy.

The Path Toward FRIB

(a) Facilities

With FRIB as a long-term goal, it is crucial that the existing facilities, including university laboratories, remain competitive. These facilities focus on the different facets of research in nuclear structure and nuclear astrophysics and provide a broad and coherent program. They will continue to provide exciting, cutting-edge scientific results for years to come, and their R&D efforts have a history of pioneering techniques, equipment, and instrumentation. In short, the science that they address and the developments that they pioneer will ultimately result in an optimized FRIB. Among the existing facilities figure the accelerators and detectors for the low-energy nuclear astrophysics program with stable beams. These complement the FRIB efforts, and are essential to address the open questions in stellar nuclear astrophysics. The optimal utilization of all the existing facilities is crucial to maintain, and indeed grow, the community of researchers and students that will be ready when FRIB comes online.

The community has identified a path to optimally position it for the start of operations at FRIB. A number of modest upgrades of the national users facilities and of facilities at university laboratories are currently under way and others are planned. These increments in capabilities will help the field maintain a leadership position in the short term, and a competitive one in the next decade while FRIB is under construction. However, over the last decade, research programs at most, if not all of these facilities, have been affected by stagnant or declining budgets. It is imperative that sufficient funding be provided to operate the facilities, and especially the users facilities (which are all oversubscribed as factors of 2-3) efficiently and effectively.

(b) Instrumentation

The funding profile mandated for FRIB drastically reduces or even eliminates funds for new experimental equipment. Although any new facility should be equipped with state of the art instruments, the situation for FRIB differs significantly from that of other major nuclear physics facilities brought online in the U.S. recently: the major leap forward of FRIB resides in the large beam power, which will produce more exotic neutron- and proton-rich isotopes at higher intensities, not in the energy or the properties of the exotic beams. Hence, the general requirements for the detectors at FRIB are in many cases the same as those applying to the existing detectors at ANL, HRIBF and the NSCL. This suite of instruments is second to none and provides the community with many of the tools needed to start up a first rate research program with exotic beams. In addition, new devices continue to be developed at national laboratories and universities to optimize the use of the available weak, rare isotope beams. Among these figures the GRETINA project, a 1π detector that incorporates the new technology of gamma-ray tracking, and will increase the resolving power for certain classes of gamma-ray spectroscopy experiments by at least one order of magnitude.

Adequate funding for the continued development of state-of-the-art detectors at existing facilities for subsequent use at FRIB is then viewed as an essential step towards ensuring that this new facility achieves its full potential at its start of operations. To this effect, the community of FRIB users has organized itself in a number of working groups focusing on specific instrumentation.

Design and R&D activities are on-going and require further support prior to construction at an existing facility. In this context, the extension of GRETINA to the full, 4π GRETA array deserves special attention as this spectrometer will revolutionize gamma-ray spectroscopy in the same way that Gammasphere did a decade ago. As stated in the 2002 NSAC Long Range Plan, "The detection of gamma-ray emissions from excited nuclei plays a vital and ubiquitous role in nuclear science. The physics justification for a 4π tracking array is extremely compelling, spanning a wide range of fundamental questions in nuclear structure, nuclear astrophysics, and weak interactions. This new array would be a national resource that could be used at several existing stable and radioactive beam facilities, as well as at RIA". The timely and cost-effective completion of this project depends critically on the steady production of Ge detectors and on the continued availability of the highly specialized workforce currently working on GRETINA. Hence, the start of GRETA construction should begin immediately upon the successful completion of GRETINA.

The continued development of instrumentation for rare isotope beam physics is as important for nuclear astrophysics as it is for nuclear physics. In addition, for progress in nuclear astrophysics, further instrumentation improvements at stable beam laboratories are essential. Many open questions in nuclear astrophysics require complementary efforts at stable and rare isotope beam facilities, and some of the open questions can only be addressed with stable beam experiments.

(c) Theory

As discussed in point (d) below and in more detail in other sections of this report, the nuclear theory community has organized itself over the last few years in order to take a coherent approach to resolving the challenges it faces. As a result, there is a high level of enthusiasm and optimism in the nuclear theory community in view of the unprecedented opportunities for substantial progress towards the goal of arriving at a comprehensive and unified microscopic description of the structure of all nuclei and their low-energy reactions from the basic interactions between the constituent protons and neutrons. While the number of creative young scientists, who are fast becoming leaders in the revitalization of nuclear theory, has increased, the present level of manpower is insufficient to carry out the current program, let alone to take advantage of the new opportunities. Thus, the nuclear structure and nuclear astrophysics communities consider it essential to increase the U.S. nuclear theory effort, as recommended in the 2003 NSAC Theory subcommittee report. It will not only advance research in important areas of nuclear theory, but will also nurture the young scientists of today to establish a nuclear theory program that will be key to the success of FRIB.

(d) A Well Organized Community

Since the last Long Range Plan, the nuclear structure and nuclear astrophysics communities have been preparing themselves for the construction of FRIB and have expressed their aspirations and plans through a number of activities and documents. Most prominent among these is the RIA Users Organization (http://www.orau.org/ria/) which has prepared a number of white papers presenting the scientific case for the facility; the latest being the document prepared for the Rare Isotope Science Advisory Committee (RISAC) the National Academies of Sciences (http://www.orau.org/ria/pdf/RIAfinal.pdf). Under its umbrella, a number of workshops dedicated to the design of the facility and its instrumentation have been organized. Following the workshops, six working groups (http://www.orau.org/ria/experimental.htm) interested in the development of specific instrumentation have been formed.

In the past several years, the low-energy nuclear theory community has been in a self-organizing process to take a more coherent approach to addressing the nuclear many-body problem. Preparations for FRIB have led to the formation of the RIA Theory Group (http://www.orau.org/ria/RIATG/), which subsequently published the *RIA Theory Blue Book: A Roadmap* (http://www.orau.org/ria/RIATG/Blue_Book_FINAL.pdf). Another recent initiative is the SciDAC-2 collaboration: *"Towards the Universal Nuclear Energy Density Functional (UNEDF)* and a third, the establishment of the international Japan-U.S. Institute for Physics with Exotic Nuclei, *JUSTIPEN.*

Another important development in nuclear science since the last long range plan is the growing connection with other fields driven by significant investments in interdisciplinary initiatives. Especially the field of nuclear astrophysics has undergone a transformational change into a truly interdisciplinary endeavor where astrophysicists and nuclear physicists work together to tackle the key problems in the field. The Joint Institute for Nuclear Astrophysics (JINA) has been the major driver in this accomplishment, others important efforts include nucastrodata.org at ORNL, and initiatives by individual research groups. As a consequence, not only have the connections between nuclear physicists and theoretical astrophysicists greatly improved, but nuclear astrophysicists, including nuclear scientists, have begun to take a more active role in astronomical observations, for example through the JINA engagement in the SEGUE observational campaign. It is critical for the future of the field of nuclear astrophysics to continue and further broaden these developments.

(e) Education

The expertise of nuclear scientists is critical to our nation's economic welfare and security. Understanding isotope science, radiation detection, and nuclear reactions is essential to the mission of U.S. national laboratories and is critical for many industries that apply nuclear technology. Nuclear scientists also provide significant foundational expertise in related fields such as accelerator physics and nuclear engineering. The prospects for FRIB come at a time when the demand for expertise in nuclear and radiation science is increasing while the supply is decreasing. The production of nuclear science PhDs has declined over the past decade from nearly 120 per year in the 1990s to approximately 80 per year now. This decline is occurring while facing increased demands for nuclear expertise from homeland security and the energy industry, and much of the existing nuclear workforce is aging and approaching retirement. Indeed, NRC News (No. S-01-022) reported that an estimated 76 percent of the nuclear workforce will be at retirement age during the period from 2000 to 2010. Concern about the decline in the number of individuals trained in nuclear science was highlighted in "The Education and Training of Isotope Experts," a report from the AAAS presented to Congress in 1999. This report stated: *"Too few isotope experts are being prepared for functions of government, medicine, industry, technology and science. Without early rescue, these functions face nationally harmful turning points, including certainty of slowed progress in medicine and some technologies, near-certainty of shocks in national security, and probable losses in quality of health care."* Since then, the situation has become even more critical. An NSAC subcommittee on education recently estimated that the national need is between 100 and 120 nuclear science PhDs per year to meet the demand. The current rate of production is approximately 70 percent of this amount. Hence, there is a critical need to maintain, if not expand, the number of talented experts in nuclear science and, in particular, in rare isotope science. This can only be done by having forefront research opportunities for undergraduate and graduate students, as they are offered by the cutting edge low energy nuclear physics accelerator facilities currently operating and, in the near future, by the FRIB facility that will attract the most talented students into the field.

Advanced education and training in nuclear science have a long tradition of preparing early career scientists for the challenges in basic research, higher education, and meeting national needs for national and homeland security, nuclear medicine, and developing instrumentation and techniques for a wide range of industries. Historically, at least 60 percent of nuclear science PhDs have careers outside of education and basic research in our universities or national laboratories. The national need for individuals educated in the science of the nucleus manifests itself in many areas. Nuclear medicine–both diagnostic and therapeutic–has increased the duration and quality of life of many individuals. Homeland security is another area where individuals trained in the science of the nucleus are vital to the nation's interest by designing methods of detecting nuclear materials that might enter our country, developing portable radiation monitors, as well as training first responders in the use of radiation detection equipment. A related aspect of our national security is Stockpile Stewardship and the need to understand fundamental nuclear reactions, often on rare isotopes, that impact nuclear device performance.

The physics of the nucleus impacts many aspects of our lives. In this era when high technology drives the economy and when decisions of national importance demand an understanding of nuclear technology, its risks and opportunities, it is more important than ever that the public be informed about science in general and nuclear issues in particular. Scientists trained in the study of the nucleus not only contribute to the education of the next generation of nuclear scientists, but also to the education of teachers and the general public. The latter is a particularly important component of scientific literacy. As more lives are saved by nuclear medicine, more people are affected and need to know about the biological effects of ionizing radiation. It is only with a basic understanding that they can make an informed risk-benefit analysis. The need for understanding the biological effects of radiation goes beyond optional exposure such as nuclear medicine to issues fraught with misinformation and fear such as radon-based radiation. Beyond biological effects there are issues of the effect of ionizing radiation on materials and the impacts of cosmic ray damage to communications or defense satellites. And one cannot expect the public to make informed decisions (or be accepting of decisions made by public officials) about such issues as nuclear waste and energy policy without a basic knowledge of the science of the nucleus. In order to improve this very critical aspect of science literacy, we need nuclear scientists in the universities teaching the K-12 teachers of tomorrow, the undergraduates, the graduate students, and reaching out to the general public.

Recent Accomplishments

The reader will find in the write-ups of the various working groups that are part of this document detailed presentations of the major accomplishments since the last long range plan. Here, a few of these are highlighted to illustrate the impressive progress that has been made in nuclear structure, nuclear astrophysics as well as in the areas where these two fields overlap.

A. Nuclear Structure

Theory:

(a) *Ab-initio* calculations with modern description of NN forces and realistic NNN interactions achieve precision of 1-2% in the energies of states in nuclei up to A=12 (GFMC), 13 (no-core shell model) and 16 (coupled-cluster technique). These calculations allow one to understand how essential features of nuclear structure emerge from the underlying interactions.

(b) Progress was made in identifying the essential components of a universal energy density functional able to describe properties of finite nuclei as well as extended asymmetric nucleonic matter. The importance of correlations beyond the mean field is being explored.

(c) A new facet of research is the coupling of nuclear structure and nuclear reaction theory which is essential for the description of weakly bound nuclei. (wavefunctions from *ab-initio* calculations have been used in computations of radiative capture reactions for big bang nucleosynthesis and in computations of spectroscopic factors; the continuum shell model formalism has been developed for the consistent treatment of open channels, thus linking the description of bound and unbound nuclear states and direct reactions).

(d) Effective nucleon-nucleon interactions have been obtained from effective field theory and applied to nuclear structure calculations.

(e) The links with many-body theory at all scales continue to be explored in quantum dots, superconductivity in metal grains and neutron stars.

Experiment:

(a) The charge radius of ^{6}He and ^{11}Li, two halo nuclei, were measured with an accuracy of 1% through the determination of the isotope shifts. The data represent stringent tests of *ab-initio* calculations and provide information on the wavefunctions of these loosely bound systems.

(b) Strong evidence has been obtained that shell structure, the cornerstone of our understanding of nuclear structure, is strongly dependent on neutron excess. Shells at N=8, 20 have been shown to disappear in n-rich systems, and new (sub)shells have been found at N=14, 16 and 32, demonstrating that n-rich systems amplify components of the interactions that are not readily noticeable in nuclei closer to stability.

(c) Spectroscopic factors measured in one-nucleon removal reactions with exotic light nuclei probe the foundations of the nuclear shell model and highlight correlation effects beyond effective interaction theory. Recent results demonstrate that there is a strong, unanticipated dependence of the measured spectroscopic factors on the binding energy of the removed nucleon (from 20% to 90% compared to the 60% measured on stable closed shell nuclei). The reduction or enhancement is beyond that predicted by large-basis shell model calculations. Similar conclusions are obtained from elastic scattering analyses that model the correlations using the dispersive relations required by causality.

(d) A new radioactive decay mode, groundstate two-proton emission, has been discovered in the nuclei ^{45}Fe, ^{48}Ni and ^{54}Zn, hereby providing a new opportunity to investigate two-nucleon correlations and elucidate nuclear structure near the proton drip line.

(e) Doubly-magic ^{132}Sn has become a new benchmark for studies of systems with a large neutron access, with first beams of ~5 MeV/A available for experiment. First systematic studies have uncovered an unexpected evolution of collectivity with neutron number. First reaction studies have uncovered strong, unexpected enhancement of sub-barrier fusion leading to renewed optimism about the use of n-rich beams for the synthesis of very heavy nuclei.

(f) A new class of many-body symmetries has been discovered by studying nuclei around ^{152}Sm. The discovery has led, among others, to the discovery of critical point symmetries for the description of phase transitions, and to a new mapping of structural evolution across the rare earth region.

(g) Using two different experimental approaches, new constraints on the nuclear matter equation of state have emerged. The compressibility of K = 230 +/- 10 MeV derived from giant resonance studies overlaps with the value extracted from the analysis of the mass dependence of the limiting temperature in expanding nuclei (K = 233 +/- 39 MeV). Determining the isospin dependence of this quantity is the next challenge.

(h) A new frontier in spectroscopy at very high spin has been reached in the rare earth nuclei ^{157,158}Er. Collective structures in these nuclei had been shown earlier to "terminate". All states of higher angular momentum observed thus far were found to be non-collective and were understood as corresponding to multi particle-hole excitations involving nucleons from the core. With the resolving power of Gammasphere a return to collectivity has now been observed that extends to spins beyond 60ħ and is associated with large triaxial deformation.

B. __Nuclear Astrophysics__

(a) The measurement of the primordial deuterium abundance with the largest telescopes combined with the theory of Big Bang nucleosynthesis has provided a definitive inference of the baryon density of the universe. This result has recently been confirmed by observations of the anisotropy in the cosmic microwave background radiation. This represents a triumph for nuclear astrophysics and promises to be a cornerstone of future studies of cosmology and the growth of structure in the universe.

(b) Observations of the products of r-process nucleosynthesis in the early Galaxy found in halo stars have provided a tremendous amount of new information about the nature of the r-process and led to the identification of additional, previously unknown, nucleosynthesis processes. Experiments at rare isotope facilities have begun to reach the r-process path for a broad range of elements. These include the beta-decay studies of ^{78}Ni and ^{130}Cd, and the neutron transfer studies around ^{132}Sn.

(c) X-ray burst observations have led to many new discoveries such as superbursts and millisecond oscillations, while also providing data on regular bursts with unprecedented precision. Driven by these developments, major advances in theory have been made; among them the first full 1D models that include all the relevant nuclear physics. On the nuclear physics side, rare isotope experiments and stable beam measurements have been able to constrain some important reaction rates, including the critical ^{15}O(α,γ) reaction rate.

(d) New measurements of the ^{14}N(p,γ)^{15}O reaction show that the reaction rate at low temperatures is about a factor of 2 lower than previously thought. This increases the age of globular clusters, and, hence, the related estimates of the age of our galaxy, by about a billion years.

(e) Major advances have been made in the multidimensional modeling of core collapse and thermonuclear supernovae. New mechanisms for the explosion of core collapse supernovae have been explored, and calculations of the nucleosynthetic yields of both types of supernovae have been performed in realistic 3D models. Advances in nuclear theory have led to a better understanding of critical input such as electron capture reactions, neutrino opacities and the role of neutrinos in nucleosynthesis. In general, the physics involving the interplay of neutrinos and nucleosynthesis in the post-bounce supernova environment has emerged as a new and exciting field.

(f) Classical novae are purely driven by nuclear processes and pioneering work has been performed at both radioactive and stable-beam facilities to elucidate the explosion mechanism and to make a connection between models and observations. Hydrodynamic simulations have revealed details of the explosion mechanism and have resulted in more accurate predictions of nucleosynthesis. Although further experimental and theoretical work remains, our understanding of these events has dramatically improved.

(g) Nuclear physics uncertainties in predictions of the neutrino flux from the sun have largely been removed with a number of new measurements of the ^{3}He(α,γ)^{7}Be and ^{7}Be(p,γ)^{8}B reactions.

C. Technological Advancements

(a) Ion and atom traps have become widespread, powerful tools for precise measurements of properties of unstable nuclei, including direct mass measurements to 10^{-8} precision, electromagnetic moments and searches for physics beyond the standard model.

(b) Gamma-ray tracking has been shown to be practical and the first major project to build a gamma-ray tracking detector, Gretina, is underway.

(c) Current generation facilities at NSCL, HRIBF, ATLAS and elsewhere have demonstrated the power of new experimental approaches tailored to the scarce rare isotope beams available. These are generating exciting results today, and confirm that the expected science reach of FRIB is achievable.

Impact on Other Fields

In nuclear systems, all the fundamental forces hold sway, from the strong interactions that form the basic building blocks, the hadrons and the nucleon-nucleon forces, to the weak interactions that initiate stellar burning, from the electromagnetic interactions that limit the stability (to fission) of heavy nuclei to gravity that constrains the structure of neutron stars. As systems ranging from a few (deuterium, ^{3}He) to 10^{57} (neutron stars) particles, nuclear systems exhibit most of the diverse phenomena characteristic of mesoscopic systems, many of which are uniquely influenced by the dominantly two-quantum fluid nature of aggregates of neutrons and protons. Nuclei provide classic examples of the critical intellectual ideas that shape our understanding of dynamical systems including the underlying chiral symmetry of quantum chromodynamics (QCD), dynamical symmetry breaking in the deformed ground states of many nuclei, quantum chaos, first delineated in the properties of nuclear energy-level distributions, and emergent phenomena such as pairing. Hence, nuclear physics has important intellectual links to other disciplines and has a strong impact on other scientific endeavors such as astrophysics and cosmology, elementary particle physics, atomic and molecular physics, material science, medicine, and many other applications of critical importance to the nation's security and economic well-being. To maximize the impact on other fields, the timely evaluation and effective public dissemination of nuclear data needs to be ensured.

While the direct impact of nuclear astrophysics on the field of astrophysics as a whole is abundantly discussed throughout this document, the reader will also find examples of the fruitful applications of nuclear physics concepts in other disciplines in some of the working group write ups included in this report. Specifically, the reader is referred to the sections on low-energy nuclear theory and on the nuclear matter equation of state in the laboratory and in astrophysics.

Furthermore, the nuclear structure and nuclear astrophysics communities have documented their impact on other scientific disciplines in a number of documents associated with the science of rare isotopes. The reader is referred in particular to the following documents:

- The Intellectual Challenges of RIA: A White Paper from the RIA Users Community; http://www.orau.org/ria/pdf/intell.pdf

- The Science of the Rare Isotope Accelerator; a brochure from the RIA Users Community; http://www.orau.org/ria/pdf/RIAFINAL.pdf

The latter document also discusses the impact of the field in the area of economical and societal applications. In that respect, the following document is also of relevance:

- Proceedings of the Los Alamos Workshop on RIA Applications; http://www.orau.org/ria/pdf/ApplicationsWorkshop.pdf

These documents, together with the forthcoming white paper from the workshop on American competitiveness, represent valuable background information for the upcoming long plan.

Working Group Reports

I. Low-Energy Nuclear Theory

(Conveners: Thomas Duguet, Erich Ormand, and Bob Wiringa)

Summary

The Nuclear Astrophysics/Study of Nuclei town meeting was held January 19-21, 2007 for the purpose of providing input to the NSAC Long-range Planning process. During the town meeting several working groups were convened to highlight research conducted in the various subfields relevant to the Nuclear Astrophysics/Study of Nuclei community. In this report, we detail the result of the Nuclear Theory working group. Because of the organization of topics at the town meeting, this working group focused entirely on theory relating to low-energy nuclear physics (LENP). Thus, the results of this report, and its recommendations pertain only to research in nuclear structure and low-energy reactions.

The working group session consisted of two introductory presentations outlining the principal theoretical challenges in nuclear structure and nuclear reactions followed by 25 contributed talks that provided more detail on specific topics. The speakers were asked to address: 1) the compelling questions in their topic, 2) accomplishments since the last LRP, and 3) a research roadmap for the topic.

Overall, the session was highly productive, with the many accomplishments since the last long-range plan being identified and many exciting theoretical opportunities in LENP being identified for the coming decade. Significant accomplishments were reported in areas of: 1) testing fundamental two-and three-nucleons interactions through *ab initio* calculations of spectra for $A \leq 12$; 2) using chiral effective field theory (EFT) to construct systematically and connect the latter interactions to quantum chromodynamic (QCD); 3) using renormalization group (RG) methods to construct universal low-momentum interactions; 4) a factor of 100 increase in the capability of the shell model; 5) microscopic mass table, low-energy spectra and shape coexistence studies from (extensions of) density functional theory (DFT); 6) advanced calculations for multi-step direct reactions with continuum discretized coupled channels; and 7) inter-disciplinary intersections such as dilute Fermions in the unitarity limit. Some very significant opportunities for the next decade include: 1) deeper connection to QCD using EFT and lattice calculations; 2) a fundamental understanding of the three-nucleon interaction; 3) fully *ab initio* calculations for nuclei through the p-shell; 4) *b initio* applications by coupled-cluster methods to medium mass nuclei; 5) configuration-interaction calculations up to A~100; 6) link DFT to the fundamental interactions through EFT and RG methods and perform calculations with quantifiable uncertainties; 7) develop a microscopic mass table with better than 500 keV uncertainty and calculate fission barriers of neutron rich nuclei from DFT; 8) *ab initio* calculations for light-ion reactions; 9) truly microscopic description of reactions involving a single-nucleon projectile.

We remark that in the past several years the low-energy nuclear theory community has been in a self-organizing process to take a more coherent approach to addressing the nuclear many-body problem. For example, the proposed exotic-beam facility and the formation of the RIA Theory

Group, which subsequently published the *RIA Theory Blue Book: A Roadmap*. A second is the recent SciDAC-2 collaboration: "Towards the Universal Nuclear Energy Density Functional (UNEDF)". A third is the recent establishment of the international "Japan-U.S. Institute for Physics with Exotic Nuclei (JUSTIPEN)". It was apparent in the working group that there is a high level of enthusiasm and optimism in the low-energy nuclear theory community. Consequently, the overarching result arising from the working group session is that LENP Theory community feels that the next decade will offer unprecedented opportunity to make substantial progress towards our goal of arriving at a comprehensive and unified microscopic description of the structure of all nuclei and their low-energy reactions from the basic interactions between the constituent protons and neutrons.

Throughout the town meeting, one overall theme arose regarding the state of the LENP Theory community: while there is a core of creative young scientists who are already leaders in the revitalization of low-energy nuclear theory the current level of manpower is insufficient the current level of manpower is insufficient to execute the current program, much less to take advantage of the fantastic opportunities before us. The working group strongly endorses recommendations from the Nuclear Astrophysics/Study of Nuclei Town Meeting for the LRP that support the construction of a rare-isotope facility and that support for nuclear theory to address key questions in nuclear structure, nuclear reactions, and nuclear astrophysics be strongly increased. As noted in the body of this report, a world-class rare-isotope facility will deliver data that will be key to the nuclear theory program. An increase in the U.S. nuclear theory effort, as recommended in the 2003 NSAC Theory subcommittee report, will not only advance research in important areas of nuclear theory, but will also nurture the young scientists of today to establish a nuclear theory program that will be key to the success of a future rare-isotope facility.

Introduction

The Nuclear Astrophysics/Study of Nuclei town meeting was held January 19-21, 2007 for the purpose of providing input of the NSAC Long-range Planning process. During the town meeting several working groups were convened to highlight research conducted in the various subfields relevant to the Nuclear Astrophysics/Study of Nuclei community. In this report, we detail the result of the Nuclear Theory working group. Because of the organization of topics at the town meeting, this working group focused entirely on theory relating to low-energy nuclear physics (LENP). The results of this report, and its recommendations pertain only to research in nuclear structure and low-energy reactions.

Prior to the working group sessions on Saturday, a series of plenary talks were presented to the entire Town Meeting. One of these plenary talks was a general overview of nuclear theory presented by Witek Nazarewicz (UTenn & ORNL). The working group session consisted of two introductory presentations outlining the principal theoretical challenges in nuclear structure (Thomas Papenbrock, UTenn) and nuclear reactions (Ian Thompson, LLNL) followed by 25 contributed talks that provided more detail on specific topics. The speakers were asked to address: 1) the compelling questions in their topic, 2) accomplishments since the last LRP, and

3) a research roadmap for the topic. The complete program is listed in Appendix A and the talks themselves may be downloaded at: http://www-mep.phy.anl.gov/atta/dnp/program_nasn_wg.htm.

In this report, we outline the results of discussions pertaining to research plans in the LENP theory community. Sections in this report specifically outline the following central points arising from the working group:

- Compelling Questions in Nuclear Theory
- Accomplishments since the last Long-range Plan
- Nuclear theory research goals for the next five years
- Experimental data needs for Nuclear Theory program
- Recommendations

Compelling Questions in Nuclear Theory

Working in concert with the full LENP community, the low-energy nuclear theory community has largely undergone a process of self-organization in order to define its research goals as part of the process of preparing for and supporting a world-class Facility for Rare-Isotope Beams (FRIB) to be constructed in the U.S. Towards this end, theorists formed the RIA Theory Group and have been key members of the RIA Users' Organizations. As a consequence, several seminal documents, such as the "RIA Theory Bluebook: A Roadmap" (http://www.orau.org/ria/RIATG/Blue_Book_FINAL.pdf), have been prepared. The theory presentations at the working group session amplified these ideas.

Overall, the overarching goal for the low-energy nuclear theory community can be simply stated as:

> *To arrive at a comprehensive and unified microscopic description of the structure of all nuclei and their low-energy reactions from the basic interactions between the constituent protons and neutrons*

It is well recognized that this is not a new goal for the LENP community, as a fundamental understanding from the constituent protons and neutrons has been a goal for more than fifty years. However, a general consensus in the community is that because of recent advances in theory and the increased availability of high-performance computing, substantial progress towards realizing this goal can be made during the next five to ten years. Furthermore, we also recognize that "unified" does not mean that a single theoretical approach is valid for all nuclei. There is no "one size fits all" method in nuclear theory. Instead, our goal is to link all approaches to the underlying physics arising from the strong interaction between protons and neutrons and connect the latter with quantum chromodynamics (QCD). Towards this end, the powerful *ab initio*, configuration-interaction, and density functional methods that are under development now, but generally have different regions of applicability along the chart of the nuclides, all need to be linked in order to achieve a unified picture of the nucleus. It is also clear that due to the complexity of the nuclear many-body problem, some approximations in our theories are necessary. As a result, new experimental data are mandatory to fully understand both the nature of the interactions between nucleons and the validity of the approximations that we implement.

The discussion during the working group session was quite broad; spanning the inter-nucleon interaction, nuclear structure, nuclear reactions, nuclear and neutron matter, to interdisciplinary intersections. While no list of research questions can truly span the full range of research conducted in the U.S., certain key questions tend to arise frequently; spinning a common thread:

- **How do NN and NNN interaction emerge from QCD?**
  The interaction at play in the nucleus emerges from QCD as a residual strong force between colorless protons and neutrons. As such, only specific features of QCD are of importance for the interaction between point-like nucleons. In recent years, a more-explicit link between QCD and the interactions between nucleons has been made possible thanks to effective field theory (EFT), based on chiral symmetry, where a natural power counting provides a hierarchy between NN, NNN, and higher-order interactions. In such an approach, as well as for more traditional potential models based on meson-exchange, experimental data in the few-body, as well as the many-body, sector are needed in order to constrain the couplings and low-energy constants. In the future, it might become possible to constrain low-energy constants directly from lattice QCD.

- **How do NNN forces impact structure and reaction properties of nuclei?**
  While much is known about NN potentials, the same cannot be said of multi-nucleon potentials. Recent *ab initio* studies for light nuclei show that the NNN force has a significant role in determining what has classically been referred to as the "spin-orbit" properties of the nucleus. NNN forces also appear to be crucial for the stability of Borromean nuclei like ^{6,8}He, ^{9}Be, and ^{11}Li. At the few-body level, there are still significant problems in explaining low-energy scattering data, indicating both the need for improved microscopic models of NNN forces and the importance of high-quality few-nucleon data to constrain these models. Just how NNN interactions affect the properties of heavy nuclei, particularly at the limits of stability, is one of the most important questions in nuclear structure. It is, therefore, of crucial importance that in the next five years, a fundamental understanding of NNN interactions be achieved. We also need to develop good effective NN, NNN, NNNN… interactions, e.g., by RG methods, which can facilitate realistic calculations of heavier nuclei.

- **What are the limits of stability?**
  Part of understanding how nuclei are put together is discovering just what the limits are to their existence. *How much angular momentum can a nucleus sustain?* High-spin studies probe this question, providing information on the concepts of super- and hyper-deformation. *What are the limits of proton-neutron asymmetry?* This question is central to our understanding of nucleosynthesis; especially the r-process, where successive (n,γ) reactions map a path in the chart of the nuclides that is not only far from the valley of stability, but well beyond the range of nuclei that have thus far been produced in the laboratory. *What is the largest charge and atomic number that a nucleus can sustain?* The heaviest naturally occurring element is Uranium, but over the years, elements up to Z~112, and possibly heavier, have been synthesized in the laboratory. Further, theoretical predictions argue for not only the existence of even heavier elements, but also their relative stability. A major goal

of the low-energy nuclear theory community during the next five years is to use new developments in density functional theory (DFT) and high-performance computing to probe these salient questions to provide more reliable answers. Of crucial importance to this theoretical effort is the construction of rare-isotope facilities with a maximum reach towards the neutron drip-line, which will provide critical data to constrain theoretical models.

- **How does shell structure evolve with neutron number?**
  Many features of near-stable nuclei relate to the concept of “single-particle orbits” that group to form “shells” at certain magic numbers. These shells arise naturally in a mean-field picture and are due to energy gaps between the single-particle orbits. A central question is if shell-closures along these so-called magic numbers are modified in the presence of a large neutron excess. The existence and location of shell closures in neutron-rich nuclei is very important to nucleosynthesis, as they determine the r-process path and, hence, the abundance of certain elements beyond iron. An even more fundamental question is whether the mean-field picture itself remains a good starting point of the description as we go to more neutron-rich and heavier systems. While there are hints that correlations and the coupling to open channels compromise such a concept for near-drip-line nuclei, the notion of well-pronounced shell closure seems to fade away in super-heavy elements.

- **How do simple symmetries arise in complex system?**
  One of the most remarkable features of atomic nuclei is that their spectra often exhibit an astonishing degree of regularity; indicating the presence of underlying symmetries. It is remarkable that a collection of several hundred nucleons, interacting via a strong, and complicated force that has two-, and, at least, three-body components, shows such regular behavior. At present, most theoretical descriptions for these symmetries are fairly simple and schematic. Since they lack a firm microscopic foundation, they generally fail to have robust predictive power, and thus are more useful to categorize symmetries. Understanding just how these symmetries arise and how to utilize them in our studies of nuclei is a question of profound interest to nuclear theory.

- **What is the impact of the continuum on nuclear properties?**
  As we probe nuclei near the neutron drip-line, the neutron separation energy decreases, and role of open channels increases. A consistent description of the interplay between scattering states, resonances, and bound states in the weakly-bound nucleus requires an open quantum system formulation of the many-body problem, such as the continuum extension of the nuclear shell model. There are many examples of the impact of many body correlations and continuum coupling on structural properties of neutron- rich nuclei. Halos with their low energy decay thresholds and cluster structures are obvious examples.

- **Can we describe large-amplitude collective motion?**
  Large amplitude collective motion is at the heart of fascinating phenomena such as the quantum coexistence of different intrinsic nuclear shapes or nuclear fission, and represents a great challenge for nuclear theory. Nuclear fission in particular is among the most difficult process to describe from first principles. It is a quantum many-body tunneling problem whose typical time-scale changes by orders of magnitude when adding just a few nucleons. A reliable description of fission is of importance for our deep understanding of nuclear structure, for a full description of r-process nucleosynthesis, and is key to the modeling of advanced fuel cycles.

- **What is the microscopic underpinning of emergent phenomena?**
  Finite quantum many-body systems such as nuclei, metallic clusters or nanoparticles share, beyond a certain size, universal behaviors such as droplet features, shell structure, quantum phase transitions, viscosity, superfluidity, magnetic/rotational response. One question of great interest is precisely how those common phenomena emerge from the complexity of such systems when one tries to describe them in terms of their constituents and the interaction between them. Tackling such a question can help us understand how the transition from microscopic to mesoscopic and finally to macroscopic systems occurs.

- **How do nuclei react with each other?**
  Complementary to studies of the structure of nuclei is how they react. The importance of detailed theories for nuclear reactions is underscored by the fact that much of the information we have on their structure is inferred from their reactions with other nuclei. It is perhaps not an understatement to say that while a correct description of the structure of a single nucleus is very challenging, a description of the collision between two nuclei, even when one of them is only a single nucleon, is substantially more complex. As a consequence, most theories in use for low-energy nuclear reactions lack a true microscopic foundation, and, thus, fail to have adequate predictive power. Given the importance of reactions to not only the experimental program, but also to astrophysical processes, such as primordial nucleosynthesis and stellar evolution, a concerted effort needs to be undertaken to place reaction theories on a more solid microscopic foundation. The leading questions today are:

    - *Can some reactions be described from first principles?* Here we ask if recent *ab initio* theories used to describe the structure of light nuclei can be extended to include dynamic processes, such as light-ion fusion reactions prominent in stars?
    - *Can we develop detailed microscopic theories for multi-step direct reactions?* Multi-step direct reactions are central to a generalized study of nuclear reactions. They encompass neutron-induced reactions (from capture to all the inelastic channels); transfer reactions, such as (d,p); as well as breakup reactions.

- **What is the equation of state (EOS) of nuclear and neutron matter?**
  The bulk properties of nuclear systems play several key roles in physics. Of obvious importance is the equation of state of nuclear and neutron matter, which governs the properties of neutron stars, plays an important role in core-collapse supernovae, and may be

measurable in intermediate-energy heavy-ion collisions. At present, large uncertainties in the pairing interaction and the bulk symmetry energy lead to substantially unconstrained descriptions of neutron matter. From a purely microscopic point of view, it remains an open question if *ab initio* based calculations can be performed for neutron matter with NNN interactions. Also, basic questions about the EOS above saturation density remain as today since non-relativistic descriptions in terms of neutron and protons are expected to break down at a certain point. As a result, threshold densities for the appearance of strange baryons and/or partially deconfined quarks, its effect on the EOS and the consequences for neutron star and supernova models need to be understood.

- **What can nuclei tell us about other systems?**
  The atomic nucleus is just one of many interesting manifestations of the quantum many-body problem. As such, it can offer many insights into the properties of other systems. For example, in the 1980's, experiments with small metallic clusters were shown to exhibit shell structures similar to nuclei via magic numbers. Extensions of theories in use in nuclear physics, such as the Nilsson model and RPA proved quite useful in describing the properties of these materials. Currently, methods in nuclear theory are being applied to a wide range of quantum systems, such as ultra-cold atoms in harmonic traps, where the strength of the interaction between the atoms can essentially be tuned to any value. Of particular interest is the unitary limit, where the scattering length goes to infinity and the energy density is given by a universal constant times the free-particle Fermi-gas energy.

Accomplishments since the Last Long-Range Plan

One of the principal purposes of the town meeting was to identify and highlight the significant accomplishments during the time frame covered by the last long-range plan. Consequently, the overview and contributing speakers at the working group were given instructions to provide this information. In addition, the nuclear theory plenary talk by W. Nazarewicz also identified several high-level accomplishments. Due to space limitations for this report, only a condensed list of accomplishments can be given, but a full view of the accomplishments by the low-energy nuclear theory community can be found in the presentations (http://www-mep.phy.anl.gov/atta/dnp/home_nasn.htm)

- **The NN, NNN, and NNNN interactions**
  Considerable insights into the nature of the NN and multi-N interactions have been made. High-quality NN potentials from the 1990s, such as Argonne v18, CD-Bonn, and Nijmegen, were extensively tested in structure calculations for $A \leq 16$ nuclei and in few-body scattering and reactions. When coupled with multi-pion-exchange NNN interactions and consistent electroweak currents, they give a remarkably good and consistent picture of light nuclei, demonstrating that nuclear shell structure really is explained by realistic interactions between the constituent nucleons. Newer methods that are contributing additional insights are EFT based on chiral-perturbation theory and RG methods. High-quality EFT-based potentials, constrained by the symmetries of QCD, were extended up to the level of N^3LO, where they give good fits to elastic NN data with fewer parameters than the older potentials. EFT-based NNN interactions were derived up to N^2LO and tested, while NNNN diagrams at N^3LO were derived (there are no additional free parameters) and estimates of their effect on the binding

of ^{4}He were made. RG methods provide a mechanism to renormalize the potential to low-momenta. Applications of RG to the various NN potentials find a cutoff scale at which the resulting non-local potentials are nearly identical. Preliminary studies of many-body systems indicate that these universal low-momentum NN, NNN, NNNN… interactions are more perturbative than the originals and could lead to much easier computation in larger nuclei. Finally, first attempts were made to extract NN scattering lengths directly from a lattice QCD calculation, using EFT-guided extrapolations.

- ***Ab initio* calculations of nuclear structure for A ≤ 12**
  Considerable success towards an exact, first-principles treatment of light nuclei was reported from the application of the Green's Function Monte Carlo (GFMC) method and the No-core Shell Model (NCSM). With the IL2 NNN interaction, the GFMC method provides an excellent reproduction of the structure of nuclei up to A=12. GFMC predictions for the ^{6}He charge radii are in excellent agreement with a new atom trap experiment. The NCSM was extended to include three-body interactions, and calculations up to A=16 have been performed. Constraints on EFT-based NNN interactions were made. Initial coupled-cluster (CC) calculations for light systems were performed for ^{16}O. A principal result of these *ab initio* studies is that the NNN interaction not only provides extra binding, but is central to the structure of nuclei. In particular, the NNN interaction was found to be a significant component of "spin-orbit" physics in nuclei and to provide the stability of Borromean nuclei.

- ***Ab initio* calculations of low-energy nuclear reactions**
  A number of light-ion reactions were also studied with considerable success. The S-factor obtained for the astrophysically important reaction ^{2}H(p,γ)^{3}He, which is a sensitive test of exchange currents, agrees with the high-precision LUNA data at the 1% level. GFMC calculations of neutron-alpha scattering show a significant sensitivity to the NNN force; with the IL2 interaction the ^{5}He resonant and non-resonant scattering are reproduced very well. Initial extensions of the NCSM to reactions were applied to compute the S-factor for the ^{7}Be(p,γ)^{8}B reaction.

- **Configuration interaction applications**
  Due to improved software and hardware, the basis dimensions available in CI calculations increased by roughly a factor of 100. This increased capability resulted in: the development of a new interaction for use in the fp-shell, improved predictions for up to A~70 nuclei (of interest for astrophysics and weak interaction physics), improved predictions for the drip line beyond Z=8 nuclei, and improvements in predictions for proton, di-proton, and neutron emission. In addition, the development of the continuum shell model and the Gamow shell model formalisms permitted the first quantitative studies of the impact of open channels on properties of weakly bound and unbound nuclear states.

- **Towards a universal DFT**
  State of the art Skyrme or Gogny functionals were shown to be too limited regarding their spin-isospin content and needing both improved functionals better data sets and fitting strategies. First hints were obtained that tensor components are crucial regarding the evolution of nuclear shells. Microscopic DFT mass tables using state-of-the-art functionals were produced with approximately 1.5 MeV accuracy (with no phenomenological term added). Using projected-GCM extensions of DFT, quadrupolar correlations were studied systematically for the first time whereas spectroscopy and shape-coexistence phenomena studies were performed for systems of particular interest. First fully microscopic calculations of various multipole strength through QRPA extensions of DFT were carried out.

- **Multi-step direct reactions with continuum discretized coupled channels**
  Converged results have been obtained for both the Nuclear and Coulomb breakup of two-body projectiles, and core transitions within continuum states have been calculated.

- **Properties of Fermi systems in the unitarity limit**
  Inter-disciplinary studies with methods routinely used in nuclear many-body applications were reported. Of particular interest were Fermi systems close to the unitary limit where the large scattering length of the interaction between the constituents leads to an energy density and a pairing gap proportional to the free-particle Fermi-gas energy. Several methods used to study nuclei were applied to that problem in order to pin down the universal proportionality constants; e.g., quantum Monte Carlo calculations led to the prediction $E/A \sim 0.44 E_{FG}$ and $\Delta \sim 0.99 E_{FG}$.

- **Quantum phase transitions in mesoscopic systems**
  Phase transitions in nuclei and nanoparticles were studied using the shell model Monte Carlo method. It was found that the heat capacity as a function of temperature behaves in a very similar way as one goes through the fluctuation-dominated normal-superfluid phase transition. Typical patterns for odd and even systems were highlighted and were confirmed by experiment.

Nuclear Theory Research for the Next Five Years

In this section, we list several important research goals that were articulated during the working group session. The list, while not complete, is generally representative of the community, and is a result of a planning process within the community, for example, the *RIA Theory Blue Book: A Roadmap.*

- **Fundamental understanding of the NN and multi-N interactions**
  The possibility of connecting the NN interaction more directly to QCD by lattice simulations is an exciting prospect. Further improvements in our understanding of the NNN interaction, which plays an important role in multi-nucleon scattering, ground- and excited-state energies, the ordering of certain levels, and transition amplitudes of spin operators, should be possible using EFT and meson-exchange theory combined with accurate calculations of structure and

reactions in light nuclei. In parallel, the role of realistic NN and NNN interactions on properties of heavier nuclei is of crucial interest and tools such as RG methods hold the promise of making microscopic calculations of such systems much easier.

- **Complete/benchmark fully *ab initio* studies p-shell nuclei**
  Computational advances in both hardware and software will make it possible to complete a full range of converged *ab initio* calculations for nuclei through the p-shell using Green's Function Monte Carlo (GFMC), no-core Shell Model (NCSM), and Coupled Cluster methods (CCM). CCM should be extendable up to A~100 nuclei with fairly realistic interactions and a new quantum Monte Carlo method, Auxiliary Field Diffusion Monte Carlo (AFDMC), is now able to evaluate systems of ~100 nucleons in a box for dense matter simulation. All these methods can and will be benchmarked against each other to validate their results.

- **Configuration interaction**
  - **Develop software to complete full CI calculations to A ~ 100:** This will lead to extensive nuclear structure studies, including: evolution of shell structure along the Z=20 and N=20, 28, and 50 boundaries; the properties of rp-process nuclei; and accurate calculations of 0ν β-decay matrix elements for ^{76}Ge and ^{82}Se. An effective interaction for the fpg shell will have to be developed.
  - **Link with *ab initio* methods to determine the effective Hamiltonian:** Here, utilizing *ab initio* methods, such as NCSM, can give guidance to derive the shell-model effective interaction from the fundamental NN and NNN force. Of critical importance is to understand how a CI calculation which would require more than ten shells and three-body interactions in an NCSM calculation can give accurate results, relative to experiment, in a single major shell with an empirical two-body interaction. In addition, the contribution of NNN interactions to effective single-particle energies and their evolution with isospin must be understood.
  - **Role of the continuum on nuclear spectroscopy:** A full implementation of CI with continuum states will address how the proximity of open channels influences the properties of weakly bound and unbound nuclear states; how Borromean systems can bind. Of particular importance will be the development of reliable effective interactions in the presence of the coupling to the continuum. The inclusion of continuum states will permit in particular a more fundamental study of the spectroscopic properties, such as the so-called spectroscopic factor.

- **Density functional theory from the Scidac-2 and complementary efforts**
  Progress towards a universal form of the nuclear energy density functional will proceed through:
  - A connection to the fundamental inter-nucleon forces through RG methods, many-body perturbation theory and the application of the density matrix expansion. Such a connection will allow one to perform calculations of experimentally unknown nuclei with quantifiable uncertainties.

  - The use of new data in neutron rich nuclei to pin down the isovector nature of the functional. Such data will be used together with improved fitting algorithms.
  - The formalization of symmetry restoration and GCM-like configuration mixing calculations *within* a truly energy functional approach.
  - From this will follow: mass tables with better than 500 keV accuracy, studies of the evolution of shell structure and of the role played by tensor/NNN/spin-orbit/time-odd/pairing components of the functional, studies of the properties of r-process nuclei, guidance for the experimental studies of super-heavy nuclei, calculations of fission barriers and mass splits, calculations of low energy spectra and decay from multi-coordinates projected-GCM calculations.

- **Apply AFMC and moment methods to compute level densities**
  Density of states with fully realistic interactions for nuclei approaching A~100 can be calculated using auxiliary-field Monte Carlo (AFMC) and moment methods.

- **Inclusion of the NNN interaction in calculations of the EOS for neutron matter**
  Extend current studies of the EOS of nuclear and neutron matter to include most recent NN and NNN interactions and calculate spin-polarized matter. Together with other inputs, such predictions will be used to benchmark improved energy density functionals below and around saturation densities. At higher densities, threshold densities for the appearance of strange baryons and/or partially deconfined quarks must be pinned down. The accompanied softening of the EOS reflects properties of nucleon-hyperon and hyperon-hyperon interactions which must be better understood.

- **Symmetries and shape transitions**
  The goal of symmetry based descriptions is to produce a microscopic underpinning of the collective structure and symmetries displayed by nuclei. This allows the categorization shape transitions over the nuclear charts. To become a predictive tool that can be utilized in the studies of nuclei, those methods must be combined with more quantitative approaches. Thus, the fermionic symmetries identified using algebraic models will be integrated into large scale *ab-initio* calculation, e.g., Sp(6,R) basis for NCSM calculations with realistic NN and NNN interactions.

- **Reaction theory**
  - ***Ab initio* calculations for light nuclei:** Apply extensions of GFMC and NCSM to dynamical processes to describe scattering and reactions of light nuclei. This will permit accurate calculations of excited-state widths, electroweak transitions, and astrophysical S-factors.
  - **Microscopic calculation of the optical potential:** Utilize structure information from DFT to develop a fully microscopic description of the optical potential (in particular, for low incident energies), and apply to (n,γ) reactions.

  - **Describe equilibration processes:** Extend optical potential studies to understand the physics of transitioning from excitations populated in direct reactions to the compound nucleus, and emission of particles and photons.
  - **Sufficient theory for direct reactions to extract spectroscopic information:** Sufficiently accurate theory of direct reactions for extracting spectroscopic information from experiments, including analysis of interference effects from higher order processes.

Experimental data needs for the future of the low-energy Nuclear Theory program

Over the next decade, and well after the construction of a new rare-isotope facility, experimental data will play a key role in the nuclear theory program. At present, insufficient knowledge exists to fully understand the effective Hamiltonian for heavier nuclei, particularly in systems with a large proton-neutron asymmetry. Data from experiments will be required to help develop a universal energy-density functional (UNEDF), as well as to test the limits and validity of our approximations. A representative list of data needed by the low-energy nuclear theory community is:

- **Charge radii and form factors to test *ab initio* predictions**
  Measurements of charge radii and electromagnetic form factors in light nuclei, including N>>Z nuclei, offer a stringent test on *ab initio* theories and convergence methods. Very precise predictions can be made now and equally precise experimental numbers are required for comparison.

- **Evolution of shell structure**
  The presence of shell closures in nuclei is indicated by several properties, such as: masses and mass differences, 2^+ excitation energies and B(E2) values, and electro-magnetic moments (e.g., g-factors). Systematic data along shell boundaries is essential in order to probe shell properties to constrain theories, which will permit accurate extrapolations to nuclei not accessible to experiment.

- **DFT requires:**
  Various nuclear data along long isotopic and isotonic chains are needed to constrain the isovector part of the energy functional. More specifically, one needs (difference of) masses, measures of collectivity and of the shell evolution *in the next major shell* where predictions of currently used functionals diverge. Data on large deformations (at low and high angular momentum) and multiple strength in neutron rich nuclei will also be extremely valuable. Extending our knowledge of the limit of stability in medium mass neutron rich nuclei will put stringent constrains on the functional. In particular, data on medium-mass halo candidates at the neutron drip-line will provide valuable information on the low density part of the functional and on the gradient corrections at play in the nuclear surface. Finally, systematics of masses and spectroscopic information in transfermium nuclei will allow more reliable predictions in the super-heavy region.

- **Beta-decay and charge-exchange reactions on neutron-rich nuclei**
  Weak transition rates generally require the application of effective operators. Data on neutron-rich nuclei will be required to pin down these effective operators so that accurate calculations can be made for the r-process.

- **Transfer reactions, single-particle and pair**
  Transfer reactions provide the ability to reach excited states of exotic nuclei and test theoretical predictions of energies and single-particle structure such as the so-called "spectroscopic factors".

- **Systematic measurements of neutron radii**
  Because of the lack of systematic data on neutron radii, important components of the nuclear energy density functional are poorly constrained. This leads to a large uncertainty in the symmetry energy and unreliable predictions for the location of the neutron drip line, shell structure, and the properties of neutron matter. Measurements with parity-violating electron scattering at JLab, on ^{208}Pb, and perhaps other nuclei in the future, as well as the use of other hadronic probes with a rare-isotope facility can provide this crucial data.

It must be remarked that a new rare-isotope facility is central to the experimental needs of the low-energy nuclear theory program. This is because only a robust rare-isotope facility will provide the systematic data on long isotopic and isotonic chains that is required to constrain our theories. In addition, this facility will produce very neutron-rich nuclei, which will allow us to study the properties of neutron skins, which are the closest we can come to producing neutron matter in the laboratory. Lastly, this facility will provide unmatched opportunities to produce and study the properties of long-lived super-heavy nuclei.

Recommendations

Over the past several years, the low-energy nuclear theory community has been in a self-organizing process to take a more coherent approach to addressing the nuclear many-body problem. One example is the proposed exotic-beam facility and the formation of the RIA Theory Group, which subsequently published the "RIA Theory Blue Book: A Roadmap". Another is the recent SciDAC-2 collaboration: "Towards the Universal Nuclear Energy Density Functional (UNEDF)". A third is the recent establishment of the international "Japan-U.S. Institute for Physics with Exotic Nuclei (JUSTIPEN)". It was apparent in the working group that there is a high level of enthusiasm and optimism in the low-energy nuclear theory community. Consequently, the overarching result arising from the working group session is that the LENP Theory community feels that the next decade will offer unprecedented opportunity to make substantial progress towards our goal of arriving at a comprehensive and unified microscopic description of the structure of all nuclei and their low-energy reactions from the basic interactions between the constituent protons and neutrons.

Throughout the town meeting, one overall theme arose regarding the state of the LENP Theory community: while there is a core of creative young scientists who are already leaders in the revitalization of low-energy nuclear theory the current level of manpower is insufficient to execute the current program, much less to take advantage of the fantastic opportunities before us. In this regard, the 2013 DOE milestone to “carry out microscopic calculations of medium mass nuclei with realistic interactions, develop a realistic nuclear energy density functional for heavy nuclei, and explore the description of many-body symmetries and collective modes, and their relationship to effective forces” is at risk. A study of the DOE/NP budget indicates that support for the low-energy nuclear theory program has been relatively flat since FY01, and currently it is essentially at FY01 level, which represents a cut in real terms. Starting in FY01 and continuing through FY05, the “structure of the nucleon” program received substantial increases, which reflects significant new research opportunities offered by JLab. As reflected throughout this report, there are many new, and exciting research opportunities proposed by the low-energy nuclear theory community. In order to take advantage of these opportunities, and to prepare for a future rare-isotope facility, a substantial increase in support to the low-energy nuclear theory community is needed.

The working group strongly endorses recommendations from the Nuclear Astrophysics and Study of Nuclei Town Meeting for the LRP that support the construction of a rare-isotope facility and that support for nuclear theory to address key questions in nuclear structure, nuclear reactions, and nuclear astrophysics be strongly increased. As noted in the body of this report, a world-class rare-isotope facility will deliver data that will be key to the nuclear theory program. An increase in the U.S. nuclear theory effort, as recommended in the 2003 NSAC Theory subcommittee report, will not only advance research in key areas of nuclear theory, but will provide an essential mechanism to nurture the young scientists of today. It is these young scientists who will establish the nuclear theory program that will be key to the success of a future rare-isotope facility.

Appendix A – Working Group Agenda

Overview:

- Challenges in Nuclear Structure -- T. Papenbrock (U.Tenn)
- Challenges in Nuclear Reactions -- I. Thompson (LLNL)

Contributions:

- NN and NNN interactions -- R. Machleidt (Idaho)
- Using EFT in nuclear physics -- H. Griesshammer (GWU)
- Renormalization Group methods -- S. Bogner (OSU)
- Ab initio studies of nuclei with GFMC -- S. Pieper (ANL)
- Ab initio studies of nuclei with the NCSM -- P. Navratil (LLNL)
- Ab initio studies of nuclei with Coupled Clusters -- D. Dean (ORNL)
- Electroweak currents -- R. Schiavilla (JLab)
- Nuclear and neutron matter -- J. Carlson (LANL)
- Green's function approach to the nuclear many-body problem -- W. Dickhoff (WU)
- The future of the nuclear shell model -- B.A. Brown (MichState)
- The role of the continuum in the shell model -- A. Volya (FSU)
- Projected Shell Model -- Y. Sun (Notre Dame)
- AFMC approach to the shell model -- G. Stoitcheva (LLNL)
- Emergent phenomena and quantum chaos -- S. Frauendorf (Notre Dame)
- Universal energy density functional -- D. Furnstahl (OSU)
- Relativistic mean field approaches -- A. Afansjev (MissState)
- Microscopic theories for LACM*, including fission -- W. Nazarewicz (ORNL)
- Symmetry-based descriptions of nuclei -- M. Caprio (Yale)
- Inelastic, transfer and breakup reactions -- F. Nunes (MichState)
- Pre-equilibrium dynamics -- T. Kawano (LANL)
- Populating the compound nucleus -- J. Escher (LLNL)
- Sub-barrier reactions -- H. Esbensen (ANL)
- Predictive power on nuclear models and their application to high density matter in neutron stars and supernovae -- J. Stone (Oxford)
- Use of overlap functions -- A. Zhanov (TAMU)
- Level densities -- M. Horoi (CentMich)

II. Experimental Nuclear Structure and Reactions

(Conveners: Larry Cardman, Michael Carpenter, Alexandra Gade,
Felix Liang, and Robert Grzywacz)

Nuclear Structure in the XXI Century

The objective of nuclear structure is to understand the nature of nucleonic matter by exploring the many-body degrees of freedom of the nuclear system and examining their dependence on the number of protons and neutrons, excitation energy and angular momentum, with the ultimate goal of developing a comprehensive and unified microscopic description of all nuclei and their low-energy reactions from the basic interactions between the constituent nucleons. Understanding the fundamental many-body problem of nuclei requires a close interplay between theory and experiment. This report focuses on the latter aspect.

Steady progress in accelerator, detector and data processing technologies has provided experimental access to an ever increasing number of degrees of freedom of the nuclear system. As a result, the ability to choose probes, instruments and techniques to investigate a specific nuclear property continues to improve and the questions that are being addressed become ever more focused.

At the time of the 2002 Long Range Plan (LRP), nuclear structure defined itself through the following set of questions:

- *What are the limits of nuclear existence?*
- *How do weak binding and extreme proton-to-neutron asymmetries affect nuclear properties?*
- *How do the properties of nuclei evolve with changes in proton and neutron number, excitation energy, and angular momentum?*

To a large degree, these questions reflected a major change in emphasis: nuclear structure was beginning to take advantage of exotic, e.g., radioactive nuclei which were becoming available in increasing numbers. A renewal of the discipline followed as first experimental results provided intriguing indications of significant changes in nuclear properties in nuclei far from stability, especially nuclei with large neutron excess. Indeed, results indicated that some of the most cherished concepts of our understanding of nuclear structure break down at some level in exotic nuclei. Among these figure the concepts that (1) the charge-independence of the strong interaction makes isospin a good quantum number, that (2) the radius and diffuseness of the neutron and proton distributions are similar, that (3) magic numbers, the corner stones of the shell model, are fixed, that (4) the deformations of the neutrons and protons are similar, or that (5) valence single-particle states are only occupied at the 60% level due to correlations. In other words, adding a large number of neutrons leads to systems where the neutrons are much more weakly bound than the protons. Without a Coulomb barrier, the neutron wave functions extend much farther out in radius, increasing both the radius and diffuseness of the neutron potential, explicitly breaking the isospin symmetry, changing the ordering and spacing of single-particle orbitals, and in some cases decoupling the proton and neutron deformations. As the weakly-bound valence neutrons are, on the average, much more distantly separated, the pairing and short-range correlations can change in character, leading either to more pure mean-field behavior or to more subtle pairing effects, depending on the level density and the nearby continuum states. The fundamental point here is that we expect nuclei far from stability to be qualitatively different from their more strongly-bound stable cousins. Therefore, it should come as no surprise that when we extrapolate our well-tested models of stable nuclei to new systems far from stability by, for example, predicting either the location of the island of more stable super-heavy elements, or the properties of the nuclei involved in the r-process, our current models, at worst, fail decisively, or at best, are unreliable in their predictions.

At the same time, we now know that when we are able to do the many-body physics right, our understanding can be remarkably good. One of the major advances in nuclear physics in the past decade is that, with advancing computing capabilities and new algorithm techniques, ab-initio calculations can be done, *e.g.*, many-body calculations starting with two-nucleon forces accurately fit to two-body scattering data, and three-body forces (known to be necessary from QCD effective field theory or meson exchange theories). These calculations describe the structure of light nuclei and explain how the features of nuclear structure emerge. The primary unknown ingredient in this approach is the isospin dependence of the three-body force, since scattering experiments cannot be done on three-neutron or three-proton systems. This isospin dependence leads to an uncertainty in the mean-field spin-orbit interaction, and, thus, to our uncertainty in extrapolating to neutron-rich systems. Now that we know the many-body physics to be under control, experiments on very neutron-rich light nuclei promise to resolve this uncertainty and provide a firm foundation for evaluating the many-body approximations required to move to heavier systems.

There are two parts to understanding the nuclear system. One is to approach nuclei in terms of their fundamental building blocks (neutrons and protons) and their interactions, which should ultimately be grounded in QCD. A key step in this description is the access to very neutron-rich nuclei, so that previously unknown parts of the interactions can be determined. The other is to master how these complex objects can exhibit remarkable simplicities, such as rotational structures and giant resonances, where all nucleons act coherently. The insight gained from studying these regularities and their origins mirrors a broad spectrum of science. Again, progress in understanding the underlying dynamics requires access to exotic nuclei. It is this realization that led the NSAC sub-committee on “Guidance for Implementing the 2002 Long Range Plan” to redefine the challenge nuclear structure faces into two compelling questions:

- What binds protons and neutrons into stable nuclei and rare isotopes?
- What is the origin of simple patterns in complex nuclei?

The 2002 LRP provided a roadmap to experimentally address these questions: ultimately, the Rare Isotope Accelerator would provide the unprecedented intensities required to reach the very limits of nuclear existence over much of the nuclear landscape. In parallel with the RIA design studies, the scientific community embarked on pioneering explorations of this new territory with the available facilities and instrumentation, and a number of spectacular successes have been achieved. These have strengthened further the science case for the Rare Isotope Accelerator and a number of supporting documents (listed later in this report) have been generated by the community. This science case has received the strong endorsement of the National Academies of Sciences in their recent RISAC report. It is thus with great anticipation that the community is now directing its efforts and energies towards the realization of the Facility for Rare Isotope Beams (FRIB.)

The results presented below illustrate the significant accomplishments realized since the last LRP. Because of the many facets of the nucleus, the relevance of individual results may sometimes not be readily apparent; they are, however, listed hereafter in order to illustrate both the richness in phenomena that the nucleus provides and the fascinating challenges the nucleus pauses to a comprehensive description. At the time where we embark on a new planning exercise, these accomplishments also provide the material from which a synthesis can later be drawn. In addition, they represent a powerful testimony to the strength of the US nuclear structure community and its leadership role in the global scientific community.

Progress Since the Last Long-Range Plan

1. Evolution of Shell Structure

The evolution of the properties of the nuclear many-body system with respect to changes in proton and neutron numbers is one of the crucial questions that must be investigated to gain a qualitative and quantitative understanding of the structure of atomic nuclei. The nuclear potential and the resulting shell structure are well established for nuclei close to stability. In a regime of extreme neutron to proton ratios, N/Z, modifications to the established shell structure have been observed. Magic numbers established close to stability break down and new shell gaps appear. Such changes in the single-particle structure are driven by the spin-isospin component of the nucleon-nucleon interaction and, thus, are strongest in nuclei with a large imbalance of protons and neutrons. These effects are strongly amplified in the proximity of the drip lines where new phenomena like exotic decay modes are strongly influenced by shell effects and the coupling to the continuum. Thus, the experimental task is to measure observables that test the predictive power and validity of nuclear models on the evolution of the shell structure of the most exotic nuclei accessible in the laboratory.

Since the last Long Range Plan, significant efforts have been invested in following the evolution of shell structure in both proton- and neutron-rich nuclei. These studies have been undertaken at facilities in the US and in collaborative efforts abroad.

Limits of nuclear existence, exotic decay modes and halo structures

Establishing and understanding the limits of nuclear existence are among the most compelling goals in nuclear science: not only do they define the limits of nuclear binding, but they delineate the nuclear landscape where nuclear astrophysics processes can occur. The delineation of the drip lines is not a trivial task for theory, due to the fact that a number of effects strongly influence whether the nucleus is bound or not. Experimentally, the task is made challenging by the fact that the cross sections for producing these nuclei are extremely small. Nevertheless, significant progress has been made over the last five years in studies of the nuclei at limits of existence:

- *Neutron dripline experimentally established up to oxygen and the approach of the neutron dripline delineated further for Z>8 by the observation of ^{31}F, ^{34}Ne, ^{37}Na, ^{38}Mg.* The existence of an isotope is the most fundamental observable accessible to experiment. For example, the neutron dripline for the N = 12 isotones has been established by the non-observation of ^{16}Be and the identification of ^{31}F, the most neutron-rich fluorine isotope currently known. ^{34}Ne, ^{37}Na, and ^{38}Mg are the heaviest isotopes in the fluorine-magnesium region known to exist. These "existence proofs" required fast beams and event-by-event particle identification resulting in almost background-free measurements in the regime of pb cross sections.

- *Proton dripline established up to Z=28, for odd-Z isotopes and partially between Z=29 and Z=82.* First observation of ^{60}Ge and ^{64}Se was achieved at the A1900 fragment separator at the NSCL. During the same measurement, missing events in the particle identification determined an upper limit for the lifetime of the neighboring isotopes ^{59}Ga and ^{63}As. As few as three particles were sufficient to prove the existence of an isotope.

- *Proton radioactivity: A large number of proton emitters established for Z=51-83.* Above Z=50, a large number of proton emitters has been identified at ATLAS and HRIBF; including proton emission from highly deformed states probing the shape driving effects of nuclear orbitals at the Fermi surface near the dripline. These studies were performed with fusion-evaporation reactions (p5n, p6n) at very low cross sections: the very sensitive detection techniques involving electromagnetic recoil separators (the FMA and RMS) enabled the study of nuclei at sub-nanobarn levels. Recent observations include proton emission from ^{135}Tb, ^{121}Pr and the observation of the very short-lived proton emitter ^{144}Tm, with a half life of only 2 μsec. First evidence for proton radioactivity from the 21^+ high-spin isomer in ^{94}Ag reported from a recent GSI experiment is a highlight for exotic proton emitters below Z=50.

- *Two-proton radioactivity.* Two-proton radioactivity has been found for ^{45}Fe, ^{48}Ni, and ^{54}Zn in experiments performed at GANIL and GSI. Two-proton emission has also been observed from the highly-excited multi-quasiparticle 21^+ isomer in ^{94}Ag. The occurrence of both types of radioactivity, one-proton and two-proton, from the same nuclear state is a unique phenomenon, never observed before. In a recent experiment at the NSCL, the direct measurement of two-proton spatial correlations has been achieved. The detailed study of two-proton radioactivity probes proton-proton pairing correlations in nuclei. While the di-proton is not a bound system, correlated pairs of protons and neutrons are a common feature in nuclear matter.

- *Charge radii as benchmarks for calculations of loosely-bound systems.* The charge radius of ^{6}He has been measured with precision laser spectroscopy at ATLAS. This is the first model-independent determination of this quantity. The data represent stringent new tests of ab-initio calculations and provide information on the wavefunctions of these loosely bound systems.

- *Structure of halo nuclei*. A triple coincidence measurement following the Coulomb breakup of ^{11}Li into ^{9}Li+n+n has provided evidence for strong spatial correlations between the two neutrons in the halo. A strong, low-lying E1 excitation was observed in the breakup experiment at RIKEN. This excitation represents the strongest E1 transition ever observed at such low excitation energies. A three-body model with strong two-neutron correlations reproduces the observations.

Yrast states and low-lying collectivity in exotic nuclei

- *Measurements of the properties of ground and lowest excited states near (doubly) magic nuclei using β-decay experiments with fast beams*. Beta-decay studies are highly sensitive probes of nuclear structure, owing to their inherent selectivity. They often provide data for nuclei farthest from stability, where production rates are extremely low. Hence, β-decay data, sometimes together with mass measurements, are often the last normalization points before extending nuclear theories into the unknown. For example, the half-lives of the exotic, doubly-magic key nuclei ^{100}Sn, ^{78}Ni, and ^{48}Ni were first measured in β decay at fast beam facilities. Using β-delayed γ–ray spectroscopy, the identification of the first 2^+ and 4^+ states in very exotic nuclei is possible using event-by-event particle identification, implantation and correlation. The emergence of the N=32 shell gap in Ti isotopes was first established in this way and the systematics of the first 2^+ and 4^+ states in the neutron-rich Nickel isotopes up to ^{76}Ni has been measured with this technique as well.

- *Measurements of the properties of ground and lowest excited states near ^{78}Ni using β-decay studies of post-accelerated fission fragments.* Ranging-out techniques have been developed to perform β-decay experiments using mixed neutron-rich ISOL beams at HRIBF. A recent accomplishment is the population of the *N=48* nucleus ^{78}Zn in the β-delayed neutron decay of ^{79}Cu and the measurement of the first 2^+ level in the *N=52* nucleus ^{84}Ge, populated in the decay of ^{84}Ga. A precise energy splitting between the $s_{1/2}$ and $d_{5/2}$ neutron orbitals for the *N=51* nucleus ^{83}Ge has been determined in the β decay of ^{83}Ga.

- *Alpha decay studies near ^{100}Sn.* Recent α-decay studies at ATLAS and HRIBF in the region near doubly-magic ^{100}Sn aimed at exploiting the fine structure of the α-decay process to provide information on shell structure in the very neutron-deficient isotopes near *N=Z=50*. The superallowed character of ^{105}Te alpha decay was demonstrated. The α-decay process near doubly-magic ^{100}Sn is enhanced by the fact that the protons and neutrons the same single-particle orbitals, hereby enhancing the probability for pre-formation.

- *Single-particle and collective excitations from proton-decay studies.* By exploring fine structure in proton emission at HRIBF and ATLAS and by coupling proton decay studies with prompt γ ray studies with Gammasphere, new information has been obtained in nuclei of the A~140-150 region on the deformation of both the proton emitting state and of the daughter nucleus, and on proton-neutron couplings in the emitting state. These results probe with high sensitivity the wavefunction of the emitting state and have pointed to the unexpected role of triaxiality.

- *Low-lying collectivity from intermediate-energy Coulomb excitation (N=Z=28, N=32, heavy N=Z).* Coulomb excitation experiments with fast beams are a selective tool to identify the first 2^+ state in exotic even-even nuclei and to measure the corresponding electromagnetic excitation strength. Recent highlights are the intermediate-energy Coulomb excitation of ^{54,55,56,58}Ni, ^{52,54,56}Ti, and ^{72}Kr at the NSCL to probe the shell structure around *N=Z=28*, to study the emergence of *N=32* as a new magic number and to track quadrupole collectivity along the *N=Z* line, respectively.

- *Low-lying collectivity from sub-barrier Coulomb excitation to probe the persistence of shell gaps at N=50, N=82.* The persistence of the *N=50* and *N=82* shell gaps in $^{126\text{-}134}$Sn, $^{132\text{-}136}$Te and $^{78\text{-}82}$Ge, $^{78\text{-}82}$Se has been assessed with Coulomb excitation at barrier energies performed with ISOL beams at HRIBF. An unexpectedly small *B(E2)* strength was found in ^{136}Te, a result discussed in terms of proton-neutron configuration mixing in shell-model calculations using realistic effective interactions. The *B(E2)* transition probability to the first 2^+ state in ^{132}Sn was measured for the first time and found to be larger than the corresponding values for the neighboring ^{130,134}Sn, mirroring the situation around ^{208}Pb. The effect is attributed to an increase in the role of proton amplitudes in the wavefunctions of low excitations in the doubly-magic nucleus, when compared to its neighbors.

- *The proton-neutron degree of freedom from hadronic scattering.* Inverse-kinematics inelastic proton scattering with fast exotic beams generates the largest number of in-beam reactions to bound excited states per beam particle. The sensitivity of this hadronic probe to proton and neutron transition matrix elements provides information about the impact of neutron excess on shell structure when moving towards the neutron dripline. A recent accomplishment is the study of ^{36,38,40}Si in inelastic proton scattering using the RIKEN liquid hydrogen target at the NSCL, where first evidence for a weakening of the *N=28* shell gap in the chain of Si isotopes was found.

- *Medium and high spin states in neutron-rich nuclei from deep-inelastic scattering* High-spin states, in excess of 30*ħ,* have been populated in heavy, deformed nuclei using deep inelastic collisions (DIC). The emergence of a new shell gap at neutron number *N=32* has been studied at ATLAS in neutron-rich Cr, Ti, Sc and Ca isotopes from DIC of ^{48}Ca beams on Pb and U targets. The data provide information on the role of the tensor force and calibrate recently developed effective interactions for shell model calculations in this mass region. DIC induced by an ^{82}Se beam on Pb and U targets has been used to access the medium-spin states in *N=50* nuclei down to ^{82}Ge in order to test the shell model in the vicinity of ^{78}Ni.

- *Yrast states in very exotic nuclei via projectile fragmentation.* A recent highlight is the $\gamma\gamma$-coincidence spectroscopy of the sodium isotopes ^{30,31}Na in the “Island of Inversion”. These nuclei were populated in fast fragmentation of various projectiles, yielding complementary information on their level schemes. Projectile cocktail beams can be used and all fragmentation products are identified simultaneously on an event-by-event basis. The science reach is directly linked to the efficiency of the γ-ray detection system.

- *Identification of the first excited state in ^{101}Sn.* Using a heavy-fusion evaporation reaction, an excited state in ^{101}Sn was identified at ATLAS with the Gammasphere array and the FMA. The data provide the first experimental information on the energy separation between the neutron $d_{5/2}$ and $g_{7/2}$ single-particle orbits in ^{101}Sn.

Study of the nuclear wave function and the single-particle degree of freedom

- *Precision measurement of ground-state wave function components and test of shell closures in very neutron-rich systems.* One-nucleon knockout reactions at beam energies above 50 MeV/nucleon in conjunction with γ-ray spectroscopy of the knockout residues have been used to (i) prove the presence of a strong Z=14 subshell gap by measuring the spacing of the $d_{3/2}$ and $s_{1/2}$ single proton orbits in a chain of Si isotopes, (ii) track the descent of intruder states in the chain of Ne isotopes when approaching the Island of Inversion, (iii) probe the persistence of the *N=28 gap* in the neutron-rich nucleus ^{46}Ar, (iv) study Cr isotopes in the vicinity of *N=32*, and (v) demonstrate the breakdown of the N=8 shell gap in Be isotopes. Neutron detection in coincidence with knockout residues provides a means to track the evolution of shell structure beyond the neutron dripline.

- *First experimental evidence for a possible weakening of spin-orbit force with neutron excess.* A surprising decrease with neutron number in the binding energy difference between the $g_{7/2}$ and $h_{11/2}$ single-particle states in the $Z = 51$ antimony isotopes was established through ^{A}Sn(α,t) $^{A+1}$Sb transfer reactions. The effect has been interpreted as evidence for a change of the spin-orbit interaction with neutron excess, possibly due to the role of the tensor force. The latter has often been omitted in mean field calculations.

- *Neutron-adding transfer reactions to study the persistence of N=82.* Transfer-reaction studies in the vicinity of the doubly-magic nucleus ^{132}Sn have been performed recently at the HRIBF. These include the ^{132}Sn(d,p)^{133}Sn reaction, extending the systematics of single-neutron levels in the *N=83* isotones. In addition to the expected single-neutron $f_{7/2}$, $p_{3/2}$ and $f_{5/2}$ excitations, the $p_{1/2}$ state was observed for the first time. For light, neutron-rich nuclei, recent transfer studies include the investigation of ^{7}He and ^{9}Li via the (d,p) transfer reaction in inverse kinematics accomplished with in-flight radioactive beams produced at ATLAS. These results represent new stringent tests of ab-initio calculations.

- *Two-nucleon knockout reactions as new spectroscopic tools.* When intermediate-energy, neutron-rich (neutron-deficient) projectiles react with a light target, for example ^{9}Be, the knockout of two protons (two neutrons) proceeds as a direct reaction. The detection of coincident γ rays provides partial cross sections for the knockout to specific final states. The interplay of nuclear structure and reaction dynamics in this approach has been used to prove the existence of a strong *Z=14* sub-shell gap in ^{42}Si and to demonstrate the technique as a new tool to selectively study proton cross-shell excitations in the neutron-rich nucleus ^{52}Ca.

- *Excited-state g-factors in rare isotopes.* The recoil-in-vacuum (RIV) technique was developed at HRIBF and used to derive $|g(2^+)|$ values following Coulomb excitation of ^{132}Te at a beam rate of 10^7/s. Theoretical interest in the g factor of the 2^+ state arises from the proximity of ^{132}Te to doubly magic ^{132}Sn. The g factor is predicted to increase as proton contributions to the 2^+ excitations become more important. The experimental result indicates a modest increase between ^{130}Te and ^{132}Te. The high-velocity transient field (HVTF) approach was developed at the NSCL and used to measure the g-factor of the first excited 2^+ states of ^{38,40}S following Coulomb excitation at beam rates of 10^5/s and 10^4/s, respectively. The $g(2^+)$ values of ^{38,40}S were found to fall midway between the predictions of the extreme single-particle model (spherical shape) and the hydrodynamical limit of Z/A (prolate deformed shape). The results indicate that both protons and neutrons play integral roles in defining the onset of deformation in the sulfur isotopes beyond $N = 20$.

- *Magnetic moments as indicator of changes in nuclear shell structure.* Information on the magnetic dipole moment of the most exotic nuclear species is presently obtained from β-NMR using fast exotic beams produced in projectile fragmentation. Required are pure and spin-polarized beams and a β-NMR detection system. A recent highlight is the measurement of the ground-state magnetic moment of the neutron-deficient isotope ^{57}Cu at the NSCL. The new ^{57}Cu magnetic moment result suggests a breaking of the ^{56}Ni doubly-magic core which remains a challenge for theory to explain.

Spin-isospin response of exotic nuclei

- *Giant resonance studies with exotic beam.* A recent highlight is the evidence for collective excitations at about 10 MeV in the neutron-rich nuclei ^{130,132}Sn. Such a shift of the giant dipole resonance (GDR) was expected from calculations and its experimental verification is significant for both nuclear structure and nuclear astrophysics.

- *Charge-exchange*. At the NSCL, the (t,^{3}He) reaction at 120MeV/nucleon triton beam energy has been developed into a new tool for studying the weak-interaction strengths in the electron-capture direction. Charge-exchange reactions measure Gamow-Teller strength and are thus at the interface of nuclear structure physics and nuclear astrophysics.

Correlation effects in nuclei

- *Correlations beyond effective-interaction theory.* One-nucleon knockout reactions allow for the study of proton and neutron spectroscopic strengths in unstable nuclei with large asymmetry in proton and neutron numbers. A reduction in spectroscopic strength relative to shell-model calculations has been established from (e,e′p) studies and one-nucleon knockout reactions and is attributed to correlation effects – short-range, long-range and tensor – which are beyond the effective-interaction theory that forms the basis of most modern shell-model approaches. At the NSCL, significant additional reduction in spectroscopic strength was observed for a deeply-bound neutron state in ^{32}Ar, a nucleus close to the proton dripline, while less reduction was found for weakly-bound neutron single-particle orbits in the proximity of the dripline (e.g. ^{15}C). Recent theoretical work involving the dispersive optical model to describe elastic nucleon scattering data also implies that minority nucleons become more correlated with increasing asymmetry, while the opposite is true for majority nucleons. This is in agreement with the observations from nucleon knockout reactions on exotic nuclei.

- *Spatial correlations*. The spatial correlation of two like nucleons can be studied with direct two-proton or two-neutron knockout reactions. Unlike the (p,t) pair transfer reaction, which probes the correlation associated with the $S = 0$ and (relative) $l = 0$ nucleon pairs, the sudden two-nucleon knockout has no specific S or l selection, but is sensitive to correlations in the nuclear wave function and poses stringent tests for modern-shell model calculations. Recent highlights comprise the measurements of the ^{9}Be(^{34}Ar,^{32}Ar)X, ^{9}Be(^{30}S,^{28}S)X and ^{9}Be(^{26}Si,^{24}Si)X two-neutron knockout reactions at the NSCL providing first evidence for the enhancement of the cross section to the 0^{+} ground state of the knockout residues due to pairing.

2. Physics and Chemistry of the Heaviest Elements

The heavy elements are a laboratory for studying nuclear dynamics and structure under the influence of large Coulomb forces. Research in this area involves ideas that are fundamental to both chemistry and physics. In the five years since the last Long Range Plan, many exciting developments have occurred such as:

- *The discovery of element 113 using cold fusion reactions and the reported synthesis of elements 113, 114, 115, 116 and 118 by hot fusion reactions.* Clearly, the most spectacular advances in heavy element research is the work by the Dubna-Livermore collaboration on the synthesis of elements 113-118 by hot fusion reactions, *i.e.*, a 4% increase in the fundamental building blocks of nature. The reported production cross sections are relatively constant with the increasing Z of the completely fused system, in stark contrast to the exponential decrease for element production in cold fusion reactions. This relative constancy is not well understood but, if confirmed, opens up exciting new vistas in our study of the chemistry and physics of the heaviest elements**.** Confirmation and understanding of these results is the most compelling scientific question for this field for the next decade.

- *The first chemistry of elements 108 (Hs) and 112*. The work on the nuclear properties of the heavy elements is intimately tied to their chemistry. Production of atoms of these elements by nuclear reactions enables chemical studies and the selectivity of chemistry allows identification of the atomic number of the species. Perhaps, more importantly, the questions being explored in heavy element chemistry are among the most profound of scientific questions, such as the form and structure of the Periodic Table and the role of relativity in understanding the fusion reactions of neutron-rich radioactive nuclei suggest enhancements in the production of longer-lived heavy nuclei of several orders of magnitude, which in turn, should enhance study of the atomic physics and chemistry of these nuclei.

- *The spectroscopy of the transfermium nuclei, leading to an improved understanding of the single-particle levels of these nuclei.* Two- and four-quasiparticle K-isomers have been found in ^{252,254}No, establishing that K is a good quantum number and therefore that the nucleus has an axial prolate shape. These quasiparticle states probe the energies of proton levels that govern the stability of superheavy nuclei, as they test quasiparticle energies from theory and thereby check predictions of magic gaps. Specifically, the position of the $2f_{5/2}$ and $2f_{7/2}$ spin-orbit partners is tested. This is important because the strength of the spin-orbit force governs the size of the possible shell gap at Z = 114.

- *The first results showing the promise of radioactive beams for heavy element research.* The HRIBF measurements of fusion of ^{132,134}Sn beams on ^{64}Ni targets exhibit an increase in cross section dependent on the neutron number of the projectile. These results together with similar data on other neutron-rich projectiles provide evidence for an as yet not understood isospin dependence of the barriers. The findings are particularly significant because neutron-rich beams are viewed as a possible way (perhaps the only way) to reach the center of the predicted island of super-heavy nuclei.

3. Collective Nuclear Structures

A remarkable feature of medium- and heavy-mass nuclei is the emergence of novel collective properties that are not apparent in few-body systems. The study and characterization of collective motion in nuclei has a distinguished history in nuclear structure. With the availability of large γ-ray arrays at both stable and radioactive ion beam facilities, the study of collective phenomena in nuclei has progressed over the last five years, and some of the physics highlights obtained from these studies are presented below:

Isospin Symmetry and Neutron-Proton Pairing in N~Z Nuclei

- *An understanding of spin-dependent charge symmetry breaking in medium-mass N~Z nuclei.* The study of medium-mass N~Z nuclei is fascinating because of the isospin symmetry afforded by equal numbers of protons and neutrons. However, this isospin symmetry begins to break down in medium-mass nuclei due to the fact that mirror partners can have very different binding energies and the Coulomb energy is rapidly rising. Such effects have recently been probed in mirror pairs reaching as high as A~50-60. By comparing differences in excitation energies of analogue states as a function of angular momentum in mirror partners to shell model calculations, a precise understanding of spin-dependent charge symmetry breaking has begun to emerge at the 10's of keV level of precision. Shell model calculations are able to reproduce these energy differences to a high-degree of accuracy and attribute them to electromagnetic spin-orbit effects, weak binding and Coulomb mixing.

- *New understanding of neutron-proton pairing in N=Z nuclei*. In nearly all nuclei, pair correlations occur between like nucleons (due to phase space arguments) and with the spins of the paired nucleons anti-aligned because of the Pauli principle (T=1, S=0 pairing). However, pair correlations in neutron-proton pairs are possible in N~Z nuclei where two modes are available, T=1, S=0 and T=0, S=1. In odd-odd nuclei, if the T=1 and T=0 pairing fields were equal and strong, the lowest states should constitute a degenerate doublet of T=1, J=0 and T=0, J=1 levels, leaving a "pairing-gap" as seen in even-even nuclei. The odd-odd nuclei of greatest interest lie between ^{56}Ni and ^{100}Sn, where the level density is sufficiently high and there are enough particles to support a robust pairing field. Experimentally, great progress has been made over the last five years on studying these odd-odd N=Z nuclei, namely, ^{66}As, ^{70}Br, and ^{74}Rb with new data emerging on even heavier isotopes. The data preclude a strong T=0 field. However, all have T=1, J=0 ground states with a clear "gap" to other configurations of about 1 MeV, apparently arising from the T=1 neutron-proton correlations.

Nuclear shapes

While mean-field calculations have proved to be a powerful theoretical tool to describe collective phenomena in nuclei, the models are not sufficiently self-consistent in transitional regions where potential energy surfaces are shallow and mixing between different shapes and configurations occur. Recently, an approach has been developed to describe such transitional regions by mixing mean-field projected wave functions that correspond to different quadrupole moments utilizing a discretized version of the generator coordinate method.

- *Spectroscopy of nuclei in oblate-prolate transitional regions.* New experimental data on excitation energies of yrast and non-yrast states and on transition matrix elements have recently been obtained for neutron-deficient Kr and Pb nuclei located in transitional regions known for shape co-existence. For example, in the isotopes ^{72,74}Kr, states built on both oblate and prolate shapes are observed while in the isotopes ^{186,188}Pb three shapes, spherical, prolate and oblate, are found to compete in energy near the ground state. Detailed spectroscopic information on states in these nuclei is now available from a variety of techniques such as in-beam γ-ray spectroscopy, β and α decay, and Coulomb excitation with both stable and re-accelerated radioactive ion beams. Due to the fact that the mixing between states of different shapes has been taken into account, these new sets of calculations can be compared directly to the experimental data on a state-by-state basis with regards to both excitation energies and electromagnetic properties. These two quantities are precisely those that measure the degree of mixing between the different shapes, and thus provide a more fundamental understanding of the competition between different shape degrees of freedom in the atomic nucleus.

- *Spectroscopy of nuclei with coexisting spherical and ellipsoidal deformation.* New studies have taken place in transitional regions where a rapid change from spherical to ellipsoidal deformation is observed. It has been suggested that such regions can be understood in terms of a transition between coexisting spherical and deformed phases. When these phases have equal energies, a phase transition occurs. Nuclei which lie at this critical point (such as ^{152}Sm) have been successfully described in terms of new analytical critical-point models, with a number of characteristic spectroscopic signatures. However, the microscopic underpinnings of such behavior remain to be explored. The new mean-field calculations described above may well offer one possibility to obtain a microscopic understanding of these critical point symmetries, and a path to describing the development of deformation in a general sense.

A long-standing question in nuclear structure physics is whether or not deformed nuclei can take on static, non-axial shapes. If the answer is positive, nuclei may exhibit new forms of collective behavior. Two types of phenomena discovered near the start of the current five year plan*, i.e.,* nuclear chirality and nuclear wobbling, postulate the existence of static triaxial shapes.

- *Chirality*. Evidence for chirality was first discovered near the beginning of the decade and appeared to be well established in the A=130 region, with ^{134}Pr cited as a classic case. However, experiments performed in the last five years have questioned this interpretation. While the evidence for chirality still exists, a simple interpretation of near degenerate partner bands as chiral pairs appears to be elusive at the moment. Possible new examples of chirality have been reported in neutron-deficient Pd and Rh nuclei as well as in neutron-rich Mo and Ru nuclei. In order to test whether these structures are truly chiral in nature, more detailed spectroscopic information is needed and could be obtained from re-accelerated radioactive ion beams.

- *Static triaxial shapes*. In the A~170 region, evidence of static triaxial shapes has been found with the identification of rotational bands associated with a one and two-phonon wobbling excitations in several Lu isotopes. A number of studies in the last five years have yielded rotational bands in other nuclei of the region with properties similar to those of the triaxial bands observed in the Lu nuclei. However, the experimental evidence suggests that these bands are built on single-particle excitations, and the identification of more wobbling phonon bands in the region has been elusive.

New collective modes

In general, collectivity in nuclei can be classified as vibrational or rotational. In deformed nuclei, rotational structures dominate, especially at high-angular momentum, and a common feature of deformed nuclei is the presence of rotational bands built on one or two-phonon states.

- *Discovery of the tidal wave excitations.* Recently, it has been suggested that multi-phonon excitations could compete energetically with rotational bands in nuclear configurations with a large angular-momentum projection on the symmetry axis of the prolate-deformed nucleus. Such configurations are well known in the A~180 region. In most instances, these so-called high-K configurations have rotational structures associated with them. A recent study of ^{182}Os has revealed the existence of a band sequence built on top of a high-K state, which is not rotational in character. This new structure is thought to result from multi-phonon γ-vibrational excitations, which have been equated with a tidal wave running on the surface of the nucleus. This past year another example of multi-phonon vibrational excitations was reported in ^{220}Th, but, in this instance, the vibrations were associated with the octupole degree of freedom. Conversely, in heavier U and Pu isotopes, *e.g.* ^{240}Pu, evidence at high-spin has been found for a transition from excitations built on an octupole vibration to states associated with a static octupole shape.

- *Reappearance of collectivity at extreme angular momentum.* The response of constituent nucleons to rotation continues to yield surprising information about the mechanisms associated with angular momentum generation. In rare-earth nuclei around N=90, it has long been observed that rotational bands exhaust their collectivity at high-angular momentum by successfully aligning their valence particles along the rotational axis. Once all valence particles are aligned (~45ħ), these bands are said to "terminate", and higher angular momentum states are created by exciting nucleons from the core. It has been a goal for many years to establish the nature of the excitations above these terminating states. Recently, a measurement at the sensitivity limit of Gammasphere has identified rotational bands in ^{157,158}Er which extend to spins beyond 60ħ. They represent the surprising reappearance of collectivity beyond band termination and appear to be associated with large triaxial deformation.

Other new and interesting results include the identification of mixed-symmetry 2^+ states in Xe and Ba nuclei, identification of anti-magnetic rotational bands in the A~100 region, a qualitative understanding of how the nucleus "cools" through the superdeformed well, competition between gamma and particle decay in deformed structures around doubly magic ^{56}Ni, identification of new K-isomers in neutron rich and trans-Fermi nuclei and new results on Pygmy resonances in neutron rich nuclei.

Opportunities for the Near Future

Although the summary of accomplishments is necessarily incomplete, it demonstrates the breadth of the activity in nuclear structure physics. In the same spirit, a few key missions per physics topic are listed that will likely be accomplished in the near future at existing facilities. Such an ambitious experimental program will require a significant amount of beam time at the present facilities.

Existence and exotic decay modes and halo structures

- Take the next steps in establishing the neutron dripline up to Z=11 by probing whether ^{33}F, ^{36}Ne, ^{39}Na and ^{40}Mg are bound,

- Study the possibility of two-neutron emission, *e.g.* for ^{26}O, by performing fragment-neutron-neutron triple coincidence measurements,

- Investigate the nature of the two-proton emission in^{45}Fe and ^{48}Ni, and study the details of the character of the two-proton emission from the 21^+ high-spin isomer of ^{94}Ag,

- Perform precision mass measurements on the most exotic nuclei to test the predictive power of nuclear models as far away from stability as presently possible.

Yrast states and low-lying collectivity in exotic nuclei

- Identify excited states in ^{100}Sn and measure the energy of single-particle states in neighboring nuclei in order to define the basic shell structure in the region,,

- Study low-lying collectivity in the proximity of conventional or newly developing shell closures far from stability with Coulomb excitation, for example in neutron-rich Si isotopes approaching ^{42}Si and the very neutron-deficient and neutron-rich Sn isotopes,,

- Probe the formation of neutron skins in neutron-rich C, S and Ar isotopes via inelastic proton scattering,

- Measure the energy ratios $E(4^+)/E(2^+)$ and search for evidence for phase transitions very far away from stability, *e.g.* in the proximity of ^{122}Pd, ^{90}Ge, and ^{148}Xe.

- Perform studies of neutron-rich nuclei to medium spins using deep-inelastic collisions of stable and re-accelerated radioactive ions on neutron- rich targets. Regions of current interest include nuclei near ^{54}Ca, ^{78}Ni and ^{132}Sn (shell evolution), ^{144}Ba (octupole deformation), and ^{106}Mo (phase transitions).

Study of the nuclear wave function and the single-particle degree of freedom

- Track the evolution of shell gaps far from stability with nucleon removal reactions by probing the restoration of the N=40 oscillator shell gap in the region of neutron-rich Ni, Cr and Fe isotopes and delineating changes in structure along the chain of N=50 isotones north of ^{78}Ni,

- Map the evolution of shell structure inside and at the western and eastern border of the “Island of Inversion” and probe the underlying driving forces via wave-function spectroscopy,

- Investigate single particle-strength by extending (d,p) reaction studies to more exotic nuclei in key regions near magic number ^{78}Ni and ^{132}Sn regions,.

- Perform g-factor measurements on rare isotopes to elucidate the interplay of collectivity and the single-particle degree of freedom in exotic nuclei near conventional or newly emerging shell gaps,

- Determine magnetic moments in the vicinity of ^{56}Ni to investigate the elusive character of the N=Z=28 doubly-magic shell closure.

Spin-isospin response of exotic nuclei

- Develop the (^{7}Li,^{7}Be) and (p,n) reactions in inverse kinematics into tools to perform charge-exchange reactions with exotic beams,
- Probe the hot GDR in fusion-evaporation reactions with reaccelerated beams,
- Study the GDR with (γ_{virt},n) virtual-photon induced reactions, the GMR using e.g. (α,α'), (d,d') scattering, and the GQR in (γ_{virt},npγ) reactions,
- Map of the $\beta-$decay strength distribution (allowed Gamow-Teller transitions) in N=Z nuclei up to ^{100}Sn and in neutron-rich nuclei by using β-delayed γ-ray as well as β-delayed neutron spectroscopy.

Correlation effects in nuclei

- Perform knockout reactions with radioactive beams in the proximity of the proton dripline to further quantify the emerging picture of reduced spectroscopic strength, as well as to elucidate the relevant physical correlations responsible for these observations,
- Gather information on the character and strength of $T = 1$ and $T = 0$ pair correlations from the (^{3}He,p) and/or (p, ^{3}He) reactions on even-even $N = Z$ ($T = 0$, $S = 0$) target nuclei,
- Study correlation effects from the use of the dispersive optical model potential applied to scattering data along long isotopic chains,
- Employ two-nucleon transfer and two-nucleon knockout reactions to probe pairing, spatial correlations, and nucleon-nucleon correlation effects in the nuclear wave function.

Studies involving the heaviest elements

- Confirm and understand the production of elements 113-118 by hot fusion reactions,
- Determine the next proton and neutron magic numbers by measuring energies of higher-lying proton and neutron single-particle states in nuclei with $Z>100$
- Study the properties of fusion induced by neutron-rich radioactive beams,
- Advance our understanding of the form and structure of the periodic table through the chemistry of heavy elements.

These goals can be achieved only with sufficient support in terms of accelerator facilities and detector systems, as discussed in detail in the facilities section of this report. Of utmost importance is the availability of sufficient experimental time with high and modest beam intensities to pursue the synthesis of the heaviest elements, transfermium spectroscopy, chemistry studies and the training of students. Many of these studies will require the availability of rare isotope beams, such as ^{36}S, ^{48}Ca, ^{58}Fe, ^{64}Ni, and ^{70}Zn. Use of heavier actinide isotopes as targets will require the continued operation of the ORNL High Flux Isotope Reactor and Radiochemical Engineering Development Center. Failure to meet the needs of superheavy element research in the United States would represent a unilateral withdrawal from one of the most exciting frontiers of science. To pursue the next step in our use of radioactive ion beams to study heavy elements, we need to develop high efficiency reaction product separators for existing RNB facilities and to develop intense beams of light ($Z< 25$) radioactive beams accelerated to Coulomb barrier energies to pursue studies of the atomic physics, chemistry and nuclear structure in very neutron-rich heavy nuclei.

Collectivity at high spins

- Study and quantify the role of triaxiality in nuclei. Both chiral doublet bands and wobbling phonon bands have been cited as evidence for static triaxial nuclear shapes, but many open questions need to be addressed before definite conclusions can be reached,

- Identify high-K, multi-quasiparticle isomers in actinide nuclei following deep inelastic collisions (DIC), to provides essential input on single-particle states and on proton and neutron pairing in the actinide region,

- Search for hyperdeformed shapes. So far, only tentative evidence exists for such shapes from studies at Gammasphere and EuroBall. Identification of such exotic shapes will not only assist in understanding shell structure at extreme deformation, but will also provide new insights on fission barriers and shape relaxation effects,

- Perform high-resolution spectroscopy of the γ-ray continuum with GRETINA to extend our understanding of hot nuclei. Correlations between *E2* γ-rays can be extracted by analyzing the ridges and quasi-continuum. These allow us to gauge the residual interactions in a region of high level density, finite temperature and high angular momentum.

New Detector Projects and Near-Future Upgrades of Current Facilities

Both new detector initiatives and the near-term upgrades of current facilities are well documented in the facilities section of this report. Initiatives or upgrades, which have significant impact on the experimental programs discussed above, are summarized below and one can refer to the facilities section for more details on the subject. Upgrades to improve RIB production include, the Californium Rare-Ion Breeder Upgrade (CARIBU), presently under construction at ANL with the aim of providing reaccelerated radioactive ion beams extracted from a ^{252}Cf fission source, plans for the SuperCARIBU upgrade aimed at increasing CARIBU intensities by an order of magnitude, plans for the installation of a turn-key electron accelerator capable of delivering a 100 kW electron beam in an energy range of 25 to 50 MeV to induce electro–fission at HRIBF, and the development of a capability to stop and extract fast-fragment beams from a gas catcher for subsequent reacceleration to 3 MeV/u at the NSCL. In order to improve beam purity of neutron-deficient fast beams produced in fragmentation, an RF fragment separator (RFFS) is currently being implemented at the NSCL.

A novel solenoid-based spectrometer HELIOS is being developed at ATLAS for reaction studies in inverse kinematics. At HRIBF, a new barrel array of position-sensitive Si detectors, ORRUBA, is being constructed for (d,p) reaction studies in inverse kinematics. Gamma-ray spectroscopy is an essential tool in nuclear structure research. A new, generation γ-ray tracking array, GRETINA, is under construction. Combining superb energy and position resolution with high-efficiency for detecting γ-rays, GRETINA is well suited for operation at either stable beam or fragmentation facilities. GRETA, the 4π version of GRETINA, will ultimately provide unmatched resolving power making γ-ray measurements involving the most exotic nuclei and the weakest reaction channels possible. Other detector systems under development include; SuperCHICO, a pixilated avalanche counter to be used in conjunction with γ-ray arrays such as GRETINA to provide kinematic reconstruction of the reaction for precise Doppler reconstruction of γ rays, a neutron detection system for the measurement of slow neutrons emerging from (p,n) reaction at the NSCL, and a system to perform Quadrupole Nuclear Resonance spectroscopy on β-emitting nuclei, β-NQR, at the NSCL.

Finally, a digital data acquisition system is presently being implemented at the NSCL to provide sub-segment resolution and, thus, γ-ray tracking capability for the highly-segmented Ge array SeGA, digital signal processing (DSP) has been implemented at HRIBF to increase the signal-to-noise ratio and to open new avenues for very sensitive correlation studies in proton, α and β-spectroscopy, and digital electronics is also being considered as an upgrade of Gammasphere in order to provide this instrument with higher count rate capability.

Long-Term Opportunities

Present day research on exotic nuclei has proven to be extremely fertile as documented in this report. Near future research will focus on resolving some of the questions raised by these recent discoveries. However, the opportunity to expand into other regions of the nuclear chart will be hampered by the limited capabilities of existing facilities. For example, recent research on neutron-rich $Z<20$ nuclei has provided the nearest access to the neutron drip line and its associated physics. The observed rapid changes in shell structure, which were initially a surprise, are now being understood better and provide a glimpse into what might be expected in heavier systems. However, a more complete understanding of how nuclei self-organize in the regime of very weak binding and of strong proton-neutron asymmetry requires the availability of intense beams of exotic isotopes over a broad range of species and energies. The future Facility for Rare Isotope Beams (FRIB) with stopped, reaccelerated and fast beam capabilities promises a qualitative advancement in our understanding of the structure of the atomic nucleus.

The scientific reach of FRIB is by now well documented in a number of white papers and documents that can be found on the web site of the RIA Users community (http://www.orau.org/ria/pubs.htm). These are:

- The Science of he Rare Isotope Accelerator; a brochure from the RIA Users Community: http://www.orau.org/ria/pdf/RIAFINAL.pdf
- A Broader Context of RIA: http://www.orau.org/ria/pdf/intell.pdf
- RIA Theory Road Map: http://www.orau.org/ria/RIATG/Blue_Book_FINAL.pdf
- RIA Physics White Paper: http://www.orau.org/ria/pdf/ria-whitepaper-2000.pdf
- RIA Facility Pre-conceptual design: http://www.orau.org/ria/oldria/p-1-0-4.pdf

Other crucial documents discussing the facility and its science are:

- 2002 NSAC Long-Range Plan: http://www.sc.doe.gov/np/nsac/docs/LRP_5547_FINAL.pdf
- Department of Energy 20-Year Science Facility Plan: http://www.sc.doe.gov/Sub/Facilities_for_future/facilities_future.htm
- NSAC Report on Comparison of the Rare Isotope Accelerator (RIA) and the Gesellschaft für Schwerionenforschung (GSI) Future Facility http://www.sc.doe.gov/np/nsac/docs/RIA-GSI-nsac-022604.pdf
- A Vision for Nuclear Theory NSAC Report: http://www.sc.doe.gov/np/nsac/docs/NSAC_Theory_Report_Final.pdf
- NSAC Education subcommittee report: http://www.sc.doe.gov/np/nsac/docs/NSAC_CR_education_report_final.pdf
- Interagency Task Force: A 21st Century Frontier for Discovery: The Physics of the Universe: http://www.ostp.gov/html/physicsoftheuniverse2.pdf

In terms of nuclear structure, the main general questions that FRIB will help us to answer are:
- How do protons and neutrons make stable nuclei?
- What is the origin of simple patterns in complex nuclei?
- What are the heaviest nuclei that can exist?

III. Experiments with Hot Nuclei, Dense Matter

(Conveners: William Lynch, Lee Sobotka, and Sherry Yennello)

In the next ten years, investments in nuclear science can provide means to address some of the most important questions regarding neutron-rich nuclei, nuclear matter and neutron stars. Participants in the session on Experiments with Hot Nuclei, Dense Matter at the Town Meeting on Nuclear Structure and Nuclear Astrophysics identified a number of compelling scientific objectives. These objectives are discussed below.

Principal Scientific Questions and Opportunities for the Next Decade

- *The EOS of asymmetric matter*
  The nuclear Equation of State (EOS) is a fundamental property of nuclear matter. It describes the relationships between the energy, pressure, temperature, density and neutron/proton (isospin) asymmetry $\delta = (\rho_n - \rho_p)/\rho$ for a nuclear system. Ground-state properties of nuclei and their isoscalar collective vibrations have constrained the nuclear EOS for isospin symmetric matter near saturation density. Measurements of collective flow and kaon production in energetic nucleus-nucleus collisions have extended the constraints on the EOS for symmetric matter to densities approaching five times saturation density. These constraints are a major accomplishment that was achieved since the last long-range plan. In contrast, the extrapolation of the EOS to neutron–rich matter, which is governed by the density dependence of the symmetry energy, has comparatively few experimental constraints.

  The EOS of asymmetric matter governs many properties of neutron stars and of type II supernovae that were also extensively discussed during the session on the Nuclear Matter EOS in the Lab and in Astrophysics. Theoretical calculations of these properties depend very strongly on the density dependence of the symmetry-energy term in the EOS.

  Reaction simulations have demonstrated the sensitivity of a number of observables to the density dependence of the symmetry energy. Some of these observables have been explored since the last long-range plan. Measurements of isotope production, isospin diffusion and the asymmetry dependence of the isoscalar giant monopole resonance (ISGMR) have provided first constraints on the symmetry energy at sub-saturation density. Continued work in these areas, as well as the PREX experiment at JLAB (which should measure the difference between neutron and proton matter radii in ^{208}Pb) will provide further constraints at and below the saturation density. Constraints at supra-saturation densities can be expected from measurements of pion production, neutron vs. proton emission and flow.

  For most of these observables, the sensitivity to the symmetry energy can be maximized by comparing systems with very large neutron-to-proton asymmetries to those with small asymmetries. First experiments of the density dependence of the symmetry energy have utilized stable beams. The use of secondary radioactive beams will increase the 'lever-arm' and thus sensitivity to the symmetry term in the EOS. This work can be executed via a coordinated strategy that employs the facilities at TAMU and the NSCL, for measurements between 20 MeV/u < E < 120 MeV/u, and the RIBF facility at RIKEN for the range 250 MeV/u < E < 300 MeV/u. Progress in this field can be greatly accelerated by the availability of intense rare isotope beams with energies 20-180 MeV/u from an FRIB facility and the construction of a TPC for precise pion measurements.

- *The role of correlations and the effective mass in asymmetric matter*
  The study of nuclei involves both the study of nuclear interactions as well as the study of the dynamics and correlations these interactions induce. There are many-body systems for which an independent particle model (IPM) provides a nearly complete explanation of the subject, others for which an IPM merely provides a convenient heuristic starting point and still others for which an IPM provides little insight. Isolated atoms and condensed matter ^{3}He are examples of the first and last categories. The IPM provides a starting point for calculations of nuclei and nuclear matter, but the accuracy of this starting point, and even the accuracy of large-basis shell model calculations, appears to depend on the n/p asymmetry.

  Recent studies of knockout reactions (on radioactive species) indicate that the spectroscopic factors are reduced when the transferred nucleon is a minority species (e.g neutrons in a proton-rich nucleus) and enhanced when the transferred nucleon is a majority species (e.g neutron in a neutron-rich nucleus) and that the reduction or enhancement is beyond that predicted by large-basis shell model calculations. Similar conclusions are obtained from elastic scattering analyses that model the correlations using the dispersive relations required by causality. This trend may be partly a consequence of the coupling of the nucleonic single-particle motions to collective excitations as well as the larger strength of the n-p interaction as compared to the n-n or p-p interactions.

  Elastic scattering provides a probe of such correlations. From such measurements, one can obtain quantitative information about the correlations that are reflected in the isospin, momentum and frequency dependent complex optical potential. Analyses with dispersive optical potentials provide the isospin dependence of the nucleon effective masses, from which one can determine the influence of the effective mass or non-locality on the EoS for neutron-rich matter and on the reaction rates through the density of states, as well as predict reductions in the spectroscopic factors for transfer and knock-out cross sections far from stability.

  To address these questions, knock-out, transfer and elastic scattering measurements with radioactive species with 15 MeV/u ≤ E ≤ 150 MeV/u are needed. Furthermore elastic neutron scattering must be done on rare but stable isotopes. Examples of experiments in the Ca region that can be done with present and future facilities are proton and neutron knock-out on ^{36,38,40,50,52}Ca, proton elastic scattering excitation functions on ^{38,50}Ca and neutron elastic scattering on ^{48}Ca.

- *Incompressibilities of Asymmetric Nuclear Matter*
  The incompressibility of nuclei and nuclear matter is a quantity of fundamental interest, with important ramifications for astrophysical systems. It describes the functional dependence of binding energy on density as systems evolve away from saturation density, and is directly connected to the energies of the compressional-mode giant resonances – the giant monopole resonance (GMR) and the ISGDR. Recent giant resonance measurements have determined this value to be $K_\infty = 230 \pm 20$ MeV.

  The dependence of the incompressibility of a nucleus, K_A on asymmetry has an important influence on the relationship between K_A and the corresponding K_∞ that describes the incompressibility of nuclear matter. This relationship can be illustrated by the leptodermous expansion:

$$K_A \approx K_\infty + K_{Surf} A^{-1/3} + K_{asym}([N - Z]/A)^2 + K_{Coul} Z^2 / A^{4/3}$$

Here, K_{asym} reflects the contributions of the density dependence of the symmetry energy to the finite nucleus compressibility. To determine K_{asym} with precision sufficient to address its influence on extractions of K_∞ and to probe the density dependence of the symmetry energy near saturation density, it is crucial to make measurements over a large range of (N-Z) values. Such an accurate determination is possible only with intense rare isotope beams that could be provided by an FRIB facility.

There also is the intriguing possibility of the observation of the "soft GMR" akin to the soft GDR observed in the halo nuclei. Thus, one would be looking at two nuclear incompressibilities: one for the "core", the other between the core and the "halo" or the "skin". Indeed, recent calculations by have indicated a threshold effect in the monopole response, resulting in considerable GMR strength at low energies, in nuclei far from the stability line.

With beam intensities of 10^6–10^7 particles per second, and target thicknesses of a few mg/cm^2, it would be possible to obtain sufficient data to identify the GMR strengths in an experimental run of about 10 days. A large number of beams with such intensities will be available at an FRIB machine with the capability of producing ions at energies of 50 MeV/u. With the projected intensities of FRIB it would be possible to make measurements on the Sn isotopes in the range A = 108–136 (N/Z ratios of 1.16–1.72).

An indirect confirmation of the incompresssibilities for nuclear matter can come from measurements of the limiting temperature. This technique uses a relationship between T_C and K. Measurements done for near symmetric nuclear matter agree with the incompressibility from the GMR. Limiting temperature measurements from reactions induced by radioactive beams could test this relationship off of beta stability.

- *The exploration of the asymmetry dependence of fission barriers*
  Fission barriers and fission probabilities reflect a balance between the Coulomb force and nuclear attraction. Fission barriers have long been included as experimental constraints on widely used macroscopic models like the Finite-Range Liquid Droplet Model. Fission saddle-point and ground-state binding energies both enter into the computation of fission barriers and both evolve as the asymmetry is varied. Experimental constraints on this evolution and on the isospin and deformation dependent level densities are needed to predict the fission rates of nuclei far from stability.

  The fission decay rates for rare isotopes are important for r-process nucleosynthesis predictions, where fission terminates the process and the fragments from fission become fresh seed nuclei for new r-process cycles. Beta-delayed and neutrino-induced fission can also play a role in limiting the r-process yields of thorium and uranium isotopes that are interesting cosmological chronometers. Furthermore, neutrino-induced fission during freeze-out has been proposed to partially correct the abundance trough observed around A = 110−120 in the r process. In order to determine the role of these different fission aspects in the r-process, measurements of fission barriers and fission-fragment distributions over a wide range of neutron-rich nuclei are crucial. However, as most of these fissionable nuclei lie outside of the domain where direct measurements can be performed, accurate extrapolation from measurements closer to the valley of stability is required.

Measurements of fission barriers with fast rare isotope beams can provide an empirical basis for improved extrapolations of ground-state and fission saddle-point binding energies away from the valley of stability. Intensities for fast beams of neutron-deficient uranium isotopes from an FRIB facility which are sufficient to measure fission barriers out to the proton dripline would more than double the isotopic range presently used to determine the asymmetry dependence of the fission-barrier heights.

While some measurements can be performed with reaccelerated beams, fast beams with energies of $20 < E/A < 150$ MeV allow measurements with thick passive or active targets and consequently can be performed with lower intensities ($\sim 10^4$ s^{-1}) than those required for experiments with reaccelerated beams (10^6 s^{-1}). The use of a Time Projection Chamber (TPC) as a thick active target may permit particularly accurate and efficient measurements of fission barriers, while allowing for the detection of charged particles with efficiencies close to 100%. The addition of large fast-neutron detectors can provide complementary information about the excitation energy of the fissioning system with efficiencies approaching 70%.

- *Understanding the low density EOS and the contribution of clusters*
  At sub-nuclear densities, correlations and clusters are an important aspect of nuclear matter that, for large systems, is reflected as a mixed phase of gas, clusters, and heavier nuclei. Simulations of core-collapse supernovae depend on properties of low-density nuclear material at densities of $10^{-1}n_0$ -$10^{-3}n_0$ and temperatures 1-10 MeV, where clusters are important. Such temperatures and densities can be achieved in near Fermi-energy heavy ion collisions. Indeed, the theoretical descriptions of nuclear multi-fragmentation and of matter near a supernova shock front are quite similar, and comparisons have been made between cluster yields measured in laboratory experiments to those calculated by models developed for the description of clustered matter in supernova explosions. Such comparisons will be refined and made more quantitative during the time scale of the present long-range plan.

  Theoretical descriptions of the fragmented nature of matter near a supernova shock front are subject to large uncertainties. Measurements of multi-fragmentation reactions have probed the liquid-like to gas-like transition for finite systems of moderate asymmetry, but extrapolations of the present day information to systems of larger isospin asymmetry are highly uncertain. Data from nuclear multi-fragmentation measurements over an extended range of isospin asymmetry may provide important constraints on such models. Measurements of the multi-fragmentation of ^{184}Pb and ^{211}Pb and ^{104}Sn and ^{132}Sn projectiles, at incident energies of about 180 MeV/nucleon would be ideal. After corrections for non-equilibrium effects, such data could be compared to nuclear statistical-equilibrium calculations that are being used to describe both multi-fragmentation and the fragment abundances in the matter in the vicinity of the shock front of type II supernovas.

- *Transport theory for correlated asymmetric Fermion systems*
  Theory and experiment form a symplectic pair, each leaning on the other for insight and direction. In order to maximally tighten the constraints on the EOS, intrinsically consistent energy functionals with isospin, momentum and range degrees of freedom should be employed in transport models. Enhanced predictive power of the transport theory may be gained by shifting from semiclassical to quantum approaches. In parallel, observables that are strongly influenced by fragment production require improved treatments of fluctuations and correlations.

  Making these improvements will not only improve our understanding of the dynamics of reactions, it will improve our understanding of n-star structure and dynamics as well as produce (in all likelihood) transportable knowledge and techniques of interest to other fields.

- *Support for interdisciplinary initiatives on the EOS*
  Many X-ray observers, theoretical astrophysicists, and nuclear physicists share an intense interest in EOS of asymmetric matter and benefit greatly from initiatives that enable collaborations on the EOS across disciplinary boundaries.

What facilities and other resources are needed for realizing these opportunities? The science objectives described above require:

- *Construction of FRIB with fast rare isotope beams of 15-200 MeV/u.*
- *Support for a coordinated international effort to constrain the EOS of asymmetric matter at densities accessible at present U.S. and international facilities.*
- *Development of, and for: a TPC, difficult and or unusual targets and cost effective instrumentation*
- *Theoretical advances in transport theory for correlated Fermion systems*
- *Support for interdisciplinary initiatives and centers*

What will be the scientific impact on other fields, are there interdisciplinary aspects?

Reflecting its dominant contribution to the pressure, the symmetry energy governs the relationships between a neutron star's mass, radius and moment of inertia. X-ray observers currently are using the relationship between the neutron star radius, and its mass in attempts to determine the symmetry energy from X-ray data. In the stellar interior, matter may exist in a plethora of different phases depending on whether the symmetry energy of nuclear matter at the relevant density lowers the free energy of nuclear matter below, or elevates it above, that for the other phases.

The EOS and phase transitions in nuclear matter also play a role in the dynamics of core collapse supernovae and in the cooling of a proto-neutron star by neutrino emission. For the latter, large proton fractions can occur in the inner core if the symmetry energy increases with density rather quickly (i.e. "stiff" dependence.) This, in turn, may allow rapid cooling via the direct Urca process: $n \to p + e^- + \bar{\nu}_e$, $p + e^- \to n + \nu_e$, a process which does not require an additional nucleon to conserve momentum.

Experimental constraints on the density dependence of the symmetry energy will allow more accurate calculations of the radii, maximum masses, moments of inertia, and cooling rates of neutron stars. Terrestrial measurements will thereby provide important constraints on the interpretation of neutron star data.

Identify the major accomplishments in your area since the last long range plan.

- *Significant constraints on symmetric matter EOS*
  The shaded region in Figure 1 shows the extracted relationship, for cold nuclear matter, between the pressure and the density that are consistent with the experimental flow data. To illustrate the value of these constraints, a few representative theoretical EOS's are also shown in the figure.

- *Initial constraints on density dependence of the symmetry energy*
  Many observables have been predicted to be sensitive to the density dependence of the symmetry energy. Fragment and nucleon emission, isotope ratios, isospin equilibration (diffusion), and isospin dependence of the GMR measurements have been made and compared to theories incorporating different parameterizations of the symmetry energy. These reaction observables – combined with theoretical models - have led to initial constraints on the density dependence of the symmetry energy. This work has also helped to define what observables are the most robust with respect to different assumptions in the various theoretical frameworks.

  For example, the results of the isospin diffusion measurements are shown in Figure 2. The cross-hatched region shows experimental values for the isospin transport ratio R_i measured from isospin diffusion in semi-peripheral collisions of neutron-rich ^{124}Sn on a neutron-deficient ^{112}Sn at incident energy of E/A = 50 MeV. The circles show corresponding theoretical values for R_i, arranged from left to right in the order of increasing stiffness of the density dependence. (The circles are also color coded with reference to the inset which shows the modeled density dependence of the symmetry energy.) The intersection of theoretical and experimental values provides an indication of the range of density dependencies for which these data and calculations are consistent, which is similar to that extracted from fragment production studies. The solid green bars in the figure also summarize model calculations, with the same symmetry energies, of the radius of 1.4 solar mass neutron stars (top scale) and of the difference between neutron and proton radii for ^{208}Pb (bottom scale). These data are consistent with a value of $K_{sym} = 500 \pm 50$ MeV, similar to the value $K_{sym} = 400 \pm 100$ MeV extracted from the isospin dependence of the Giant Monopole resonance. These first constraints are sensitive to densities at or below saturation. This result needs to be cross examined by measurements using different probes, at both low and high energy, with the aid of more sophisticated theoretical models.

- *Understanding of the flattening of the caloric curve in terms of reduced mean densities of the correlated Fermion system*
- *Determination of the limiting temperature dependence on mass and excitation*
- *Measurements of reduced densities at the time of fragment emission*
- *Production of neutron-rich nuclei in deep inelastic collisions near the Fermi energy*
- *First attempts to extract how the coupling between effective masses and spectroscopic factors evolves with n/p asymmetry*

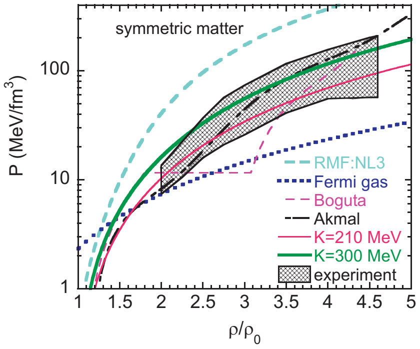

Figure 1. Laboratory constraints on the nuclear matter equation of state (from P. Danielewicz *et al.*, Science **298**, 1592 (2002)).

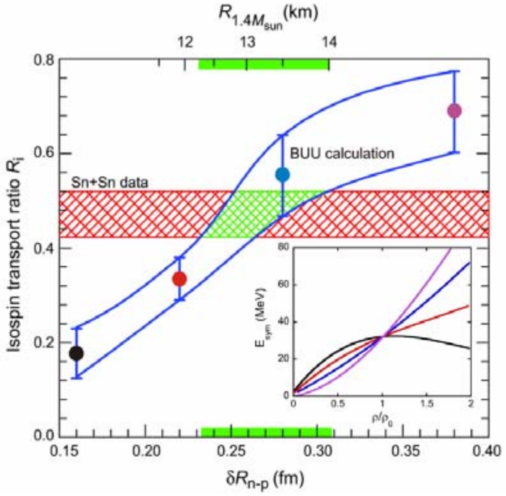

Figure 2. Comparison of the measured (cross hatched region) and calculated (solid points) values for the isospin transport ratio R_i. The top and bottom scale summarize model calculations for radii of 1.4 solar mass neutron stars (top scale) and for the difference of neutron and proton radii of ^{208}Pb (bottom scale) for those symmetry energy functions that were used in calculating the isospin transport ratio. (Data from M.B. Tsang *et al.*, Phys. Rev. Lett. **92**, 062701 (2004), calculations by B.A. Li and A.W. Steiner).

IV. Nuclear Astrophysics

(Conveners: Art Champagne, George Fuller, and Michael Wiescher)

Stellar evolution is driven by a combination of gravitation and strong, electromagnetic, and weak nuclear reactions and decays that provide or remove energy and change chemical composition. The many of the results of these nuclear processes can be observed in stellar atmospheres, in stellar explosions, in the interstellar medium and in meteoritic grains. On a larger scale, this information can be used to probe the history of our galaxy, to provide information about the early universe, and even to constrain new physics beyond the Standard Model. We have entered an exciting period where observational data challenge our community to provide new and more accurate information and theoretical models in order to build a more complete astrophysical picture. At the same time, results from nuclear physics have been the source of new astrophysical insight. Nuclear physics is a key partner in the exploration of the universe.

Progress Since the Last Long-Range Plan

There have been exciting advances in nuclear astrophysics in the period since the last Long-Range Plan:

- *The measurement of the baryon content of the universe*
  The measurement of the primordial deuterium abundance with the largest telescopes combined with the theory of Big Bang Nucleosynthesis has allowed a definitive inference of the baryon density of the universe. This result has recently been confirmed by observations of the anisotropies in the cosmic microwave background radiation. This is a triumph for nuclear astrophysics and promises to be a cornerstone of future studies of cosmology and the growth of structure in the universe.

- *The sun and the solar neutrino problem*
  A number of new measurements of the $^{3}\mathrm{He}(\alpha,\gamma)^{7}\mathrm{Be}$ and $^{7}\mathrm{Be}(p,\gamma)^{8}\mathrm{B}$ reactions have been completed that largely remove nuclear uncertainties from calculations of the flux of solar neutrinos. In addition, the $\mathrm{D}(p,\gamma)^{3}\mathrm{He}$ reaction has been measured at solar energies. Although this result is more relevant for pre-main sequence evolution, it is an impressive technical achievement.

- *The $^{14}N(p,\gamma)^{15}O$ reaction and the age of the galaxy*
  New measurements of the $^{14}\mathrm{N}(p,\gamma)^{15}\mathrm{O}$ reaction show that the reaction rate is about a factor of 2 lower than thought at low temperatures. This increases the ages of globular clusters, and thus estimates of the age of our galaxy, by about a billion years.

- *The evolution of massive stars*
  The rate of the $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ reaction directly impacts the later stages in the evolution of massive stars as well as the composition of white dwarfs, Type Ia supernovae and nucleosynthesis in Type II supernovae. A new series of direct and indirect measurements have been performed and taken together with previous studies, these results provide a more

accurate value for the *S*-factor at stellar energies. However, more work remains. In addition, measurements of $^{12}C+^{12}C$ fusion suggest an unexpected hindrance at low energies that changes the timescale for carbon burning and the ignition conditions for Type Ia supernovae.

- *Cataclysmic binaries*
  The present generation of radioactive ion-beam facilities has performed pioneering work related to classical novae. These results have been combined with hydrodynamic simulations to reveal details of the explosion mechanism and more accurate predictions of nova nucleosynthesis. Direct and indirect measurements with stable beams have also been carried out, which provide complementary information and set the stage for new radioactive-beam measurements. Observations of x-ray bursts have led to many new discoveries such as superbursts and millisecond oscillations while also providing data on regular bursts with unprecedented precision. Driven by these developments, major advances in theory have been made among them the first full 1D models that include all the relevant nuclear physics. On the nuclear physics side, rare isotope experiments and stable beam measurements have been able to constrain some important reaction rates, including the critical $^{15}O(\alpha,\gamma)$ reaction rate.

- *The r-process in metal-poor stars*
  The site of the r-process is a long-standing puzzle in astrophysics. In the past few years, a number of stars have been observed in the galactic halo that show an extreme overall deficit in their heavy-element abundance relative to the sun, yet an enhancement in the elements formed by the r-process. Furthermore, for $Z \geq 55$, the abundance pattern matches that of the solar system, with the exception of radioactive uranium and thorium, which are depleted. This reduction in uranium and thorium with respect to the solar abundance gives an estimate of the ages of these stars, which are comparable to those of the oldest globular clusters. These ongoing observations have spurred an increased emphasis on understanding the r-process and for the first time experiments at rare isotope facilities have reached the r-process to perform beta-decay studies of ^{78}Ni and ^{130}Cd, and neutron transfer measurements near ^{132}Sn. Many of the theoretical models for the r-process are sited in environments with intense neutrino fluxes (e.g., hot post-supernova neutron stars). As a result, neutrino-nucleus processes can be important and this ties nuclear astrophysics and reaction studies to the exciting developments in the experimental neutrino physics program.

- *Core collapse supernovae*
  Major advances have been made in the multidimensional modeling of core collapse and thermonuclear supernovae. New mechanisms for the explosion of core collapse supernovae have been explored, and calculations of the nucleosynthetic yields of both types of supernovae have been performed in realistic 3D models. Advances in nuclear theory have led to a better understanding of critical input such as electron capture reactions, neutrino opacities and the role of neutrinos in nucleosynthesis. In general, the physics involving the interplay of neutrinos and nucleosynthesis in the post-bounce supernova environment has emerged as a new and exciting field.

Open Questions and Opportunities

Although the synopsis above is necessarily incomplete, it demonstrates the breadth of the activity in nuclear astrophysics and its synergistic relationship to astrophysics as a whole. What are the compelling questions for the coming decade? Several panels from outside of nuclear physics have identified important problems in physics and astrophysics. For example, the National Research Council publication *Astronomy and Astrophysics in the New Millennium* (2001) lists:

- How did the universe begin, how did it evolve from the soup of elementary particles into the structures seen today, and what is its destiny?
- How do galaxies form and evolve?
- How do stars form and evolve?

Another NRC study *Connecting Quarks with the Cosmos - Eleven Science Questions for the New Century* (2003) includes:

- How were the elements from iron to uranium made?

All of these questions have an important or central nuclear-physics component. Clearly, there is general interest in the issues that we are addressing. However, we would state these questions somewhat differently and more specifically:

- What can light element and Big Bang Nucleosynthesis studies tell us about the early universe, the lepton numbers, and the first stars?
- How old are the oldest stars in our galaxy?
- How do stars evolve and what are the nucleosynthetic signatures of stellar evolution?
- What is the history of chemical enrichment in the galaxy and what does that tell us about the evolution of the Galaxy and galaxy formation and evolution in general?
- What are the sources of ^{26}Al in the interstellar medium? What other radioactivity may be detected?
- Can we link observations of classical novae to a detailed understanding of the explosion mechanism?
- What is the nuclear physics of x-ray bursts and processes occurring in the crust of neutron stars?
- What is the rate of the 12C(alpha, gamma)? Can we describe the advanced burning stages of massive stars and the conditions prior to core collapse?
- Can we build convincing models for Type Ia and core collapse (Types II, Ib, Ic) supernovae?
- What are the relevant weak interaction processes during and after core collapse?
- What is the site of the r-process? Can it be described from first principles?

Facilities and Resources – Current Capabilities

As this list demonstrates, nuclear astrophysics has grown in ambition and scope since the last Long-Range Plan. There is a diverse set of open questions that is mirrored by the diversity of nuclear information that is required to address them. In some cases, there is a single, critical reaction that must be measured. For example, the $^{12}C(\alpha,\gamma)^{16}O$ reaction governs the subsequent evolution of massive stars. At other times information about a selected set of reactions is needed in order to describe an astrophysical process. Numerous examples of this are contained in the list of open questions, but one example is classical novae where ~30 reactions play some part in the outburst and in the interpretation of observations. In contrast, extreme environments such as x-ray bursts, the r-process and supernovae require a wealth of systematic information, e.g. masses, half-lives, Gamow-Teller strengths, etc. All of this information is difficult to come by. The most interesting reactions are often the slowest because they set the timescale for the astrophysical process in question. The most interesting nuclei may be far from stability. Thus, every situation requires a variety of resources and experimental approaches.

Direct measurements of stellar reactions are long and difficult, requiring dedicated accelerators and advanced detector systems. In the U.S., this work is carried out at 3 complementary university-based facilities: CENPA (University of Washington), LENA (TUNL) and at Notre Dame. Their impact can be seen in the highlights listed above and yet continued progress is threatened by a lack of competitive modern equipment. There is a clear need for investment in accelerator and detector technology for low-energy measurements.

Indirect measurements can help to define the important reactions and at times are the only means available to study a reaction of interest. The university laboratories at Notre Dame, Texas A&M, TUNL and Yale are the venues for much of this work, but again university laboratories have suffered from lack of support in the past decade. This affects not only the scope and quality of the research being carried out, but also the educational opportunities offered to students.

Direct and indirect measurements with stable and radioactive beams are carried out at ATLAS, HRIBF and at the NSCL. Radioactive secondary beams are also available at Notre Dame, Texas A&M and at a new facility is being commissioned at Florida State University. The programs and capabilities of these laboratories have evolved in a complementary fashion. Experiments with fast beams can be carried out at the NCSL, the HRIBF produces high-quality ISOL beams, and beams produced by in-flight techniques are available at the other facilities. Active programs are underway at all of these laboratories, which take advantage of their unique combinations of available beams and experimental equipment.

By its nature, nuclear astrophysics requires multi-disciplinary effort. In the past, this has often been a passive activity, with the communities exchanging information only through the literature. However a multitude of efforts, on both a large scale (such as JINA and the Terascale Supernova Initiative) and at the group level have demonstrated the great benefits of active collaboration among the disciplines. This activity must be supported.

Students should also be included in a discussion of resources. They are drawn to astrophysics in general, often because of an exposure to astronomy as children. Nuclear astrophysics is appealing to them because of its combination of astrophysics with hands-on laboratory or computational work. It is a popular entry point into nuclear science. However, the continued erosion of support, particularly at the universities, threatens what has been an extremely cost-effective training ground for pure and applied nuclear physics.

Facilities and Resources – New Initiatives

The questions that will be addressed by nuclear astrophysics in the coming decade present technical challenges that must be met by improvements at existing facilities and by developing and implementing new capabilities. The major new initiative for our field will be the Advanced Rare Isotope Facility, which is discussed below. However, other resources are needed in the period leading up to its construction and indeed, after.

Improving the sensitivity of measurements at low energies for stellar structure and evolution will require new accelerators and advanced detectors. Work in this direction is underway at LENA and Notre Dame. The proposed CLAIRE facility at LBL has the potential to further advance the reach of low-energy measurements and could serve as a model for an underground accelerator facility.

Major improvements are planned at radioactive-beam facilities in order to advance progress in the area of stellar explosions. The CARIBU project at ATLAS will use Cf fission fragments as a source for re-accelerated n-rich beams. The addition of an electron driver at the HRIBF would also allow for intense n-rich beams (from U-fission), but with a different fragment distribution than CARIBU. There are also plans for re-accelerated beams at Texas A&M. These projects would offer new routes to the study of r-process nuclei. Re-accelerated beams at the NSCL would permit a wider range of measurements of reactions in novae and x-ray bursts and production of nuclei in the iron region that are of interest for supernovae. These projects clearly complement one another. Taken together with the ISAC facility at TRIUMF, the radioactive-beam facilities in North America offer a wide range of beams and energies. Each has unique capabilities and all are over subscribed. They will represent the state of the art for the next 5-10 years and will lead the way towards the realization of an Advanced Rare Isotope Facility.

Several, fundamentally new approaches are envisioned for nuclear astrophysics in the coming decade. Intense, high-quality γ-ray beams are produced by the HIγS facility at TUNL. These will be used initially for measurements of the $^{12}C(\alpha,\gamma)^{16}O$ reaction via its inverse $^{16}O(\gamma,\alpha)^{12}C$. Measurements related to the production of the rare p-process nuclei are also possible. The ν-SNS initiative is intended to make use of the intense, pulsed neutrino beams from the SNS to measure selected neutrino-nucleus cross-sections. These are of interest for studies of the neutrino interactions during core collapse and the r-process. The National Ignition Facility will produce stellar-like environments with extraordinary neutron fluxes. Approximately 15% of the NIF program will be devoted to basic science and the possibilities for studies of nuclear astrophysics are being explored.

The 3 new initiatives just described, along with the DOE and NSF High Performance Computing Facilities represent highly leveraged opportunities for nuclear astrophysics. The major funding for each comes from sources outside of nuclear physics. However, even "free" facilities require funding for manpower, detectors and operations.

The Advanced Rare Isotope Facility

The existing radioactive beam facilities continue to advance the science and technology of nuclear physics, but major progress towards answering many of our open questions will require an advanced radioactive-beam facility. The present versions of the Advanced Rare Isotope Facility promise a qualitative advancement in a number of key areas: Measurements of masses, half-lives, etc. on the neutron-rich side of stability will allow us to describe the r-process in detail up to the A=195 peak. On the proton-rich side, the full rp-process will be accessible via direct and indirect measurements. Many Gamow-Teller strength distributions for nuclei relevant for core collapse supernovae and neutrino-affected nucleosynthesis will be measured. These objectives provide the motivation for work that is being performed at the current facilities and a great deal will be accomplished in the next decade. However, the ultimate goals will be out of reach without an advanced facility, which we view as the culmination of many years of effort.

Fortunately, the transition to a "lower cost" radioactive-beam facility has kept the basic goals of nuclear astrophysics intact. Nonetheless, the loss of the multiple-beam capability is a cause for concern, particularly in view of the large demand for beam time at the present laboratories. An advanced facility will push the frontier beyond what is possible now, but this means that radioactive-beam experiments will continue to be difficult and time-consuming. In considering how the field will progress, it is also important to pay attention to the pace of progress.

Outlook

Nuclear astrophysics has reached a level of interest, manpower and technology that promises an upcoming period of excitement and discovery. Resources put into nuclear astrophysics are well leveraged. There has been and will continue to be considerable investment by the United States and other countries in astronomical instrumentation and in experimental facilities devoted to neutrino and other particle physics. Nuclear physics has played a key and indispensable role in the exciting advances coming from these fields.

Clearly the Advanced Rare Isotope Facility will play a critical part in the further development of the field. However, it is important to realize that this by itself facility cannot address all of our open questions, which by their very nature require other experimental approaches. This does not indicate a lack of focus, but rather is an indication of the breadth of nuclear astrophysics today. For example, stellar evolution will remain an essential area of study and the issues there can only be addressed by low-energy measurements with stable beams. Thus, an increased and continuing investment in other techniques and facilities is required. Stellar explosions are an area where the interests of nuclear astrophysics coalesce with those of nuclear structure. Likewise, the core collapse supernova problem and a number of issues in cosmology represent subjects where there is significant overlap between nuclear structure and nuclear astrophysics as well as with neutrino physics. Therefore, support for nuclear-structure and neutrino theory is essential for nuclear astrophysics as well. In addition, it is critical that the gap between experiments and observations be narrowed. JINA is an important first step in this direction, but there should be a broader focus on achieving this goal.

These requirements illustrate the multi-disciplinary character of nuclear astrophysics. It follows that investment in a suite of complementary capabilities in experiment and theory is necessary. We believe that the opportunities in nuclear astrophysics justify this investment.

V. Nuclear Structure and Nuclear Astrophysics

(Conveners: Ani Aprahamian and David Dean)

The physics of nuclei and astrophysics beautifully intersect in processes that govern the evolution of stars and element production in the Universe. Nuclear astrophysics covers a broad area of research ranging understanding nuclear material in the outer regions of neutron stars, electron capture on nuclei during supernova explosions, and masses, life time, and neutron capture cross sections on very neutron rich nuclei in the r-process nucleosynthesis path, very low-energy reaction rates in stellar processes, and rp-process nucleosynthesis including the CNO cycle and breakout from it. The interplay between theory and experiment in nuclear astrophysics also covers a broad range of exciting challenges from solving the nuclear many-body problem to a degree of accuracy that enables predictive physics, to understanding nuclear reactions on nuclei, to simulating a core-collapse supernova.

From the below discussions, it should become evident that nuclear theory impacts our understanding of astrophysical events and that nuclear experiment validates our theoretical understanding of nuclear properties that cannot be measured in the laboratory. While investigations of nuclear properties and reactions will always be driven by experiment, the need for improved theoretical understandings is driven by the copious amount of information required to make a significant impact within nuclear astrophysics. For example, the r-process path moves through nuclei from iron to uranium and would require for a complete description all masses, life times, neutron captures, neutrino induced fission cross sections, and so forth. Such a complete description of these various properties will occur only through application of theoretical methods to the regions of interest and these theoretical models need validation by data that today does not exist. This points us to new facilities such as FRIB that will test our understanding of nuclei in regions of unstable nuclei.

While theoretical and experimental investigations of nuclei impact our understanding of astrophysics, that understanding is often coupled with sophisticated simulations of the astrophysical problem being addressed. For example, simulations of core collapse supernovae require input from nuclear physics in terms of various reaction rates and the nuclear equation of state at various temperatures and densities, but the actual simulation of the collapse is, at the minimum, driven by neutrino transport through the hydrodynamically explosive environment coupled to gravity.

We outline below several areas of research where our understanding of the basic physics will be improved by continuing refinements in theory and new measurements of increasing accuracy offered by facilities such as FRIB and current low-energy nuclear facilities. Because neutrinos play an important role in both core collapse mechanisms and quite possibly in nucleosynthesis through neutrino-induced reprocessing of heavy elements in the r-process path a better theoretical and experimental understanding of neutrino-nucleus cross sections will also be required in future years. In addition, an area where an experimentally based nuclear astrophysics research program could be mounted in future years is the National Ignition Facility.

Astrophysically Interesting Cross Sections in Light Nuclei

Some of the *ab initio* methods that successfully describe bound states of nuclei can also be adapted to describe scattering and reactions at few-MeV energies. First steps toward general solution of low-energy scattering in p-shell nuclei have been taken: wave functions and cross sections for neutron scattering on ^{4}He have been computed using realistic potentials with a GFMC method that imposes a scattering-wave boundary condition. The results highlight the importance of the three-nucleon interaction, with the interaction that had been most successful in bound-state work yielding a close match to experimental data. In the coming years, this method will be tested in more-difficult cases of scattering by less-compact nuclei and nucleus-nucleus scattering. Some of these scattering problems will provide initial states for capture to a bound state, and the results will be used to compute capture cross sections. Transfer reactions, in which two nuclei exchange particles to become two new nuclei, can also be addressed using this method, but with significantly more complicated boundary conditions.

In addition to expanding the range of tests for realistic potentials and currents, this work will predict absolute cross sections of astrophysical interest. The absolute normalization of a cross section is vitally important for astrophysics, but it is also the most difficult quantity for both theory and experiment to produce. Recent successes with exact calculations in $A \leq 4$ nuclei offer the exciting prospect of reliable absolute cross sections predicted from realistic Hamiltonians and currents. Even if the *ab initio* GFMC methods never extend beyond the present $A \leq 12$ current limit, the results will be useful. Studies of big-bang nucleosynthesis and solar-neutrino mixing parameters depend on measured cross sections in this mass range, and a reliable theory could help reduce the size of the formal errors by providing additional constraints. If r-process synthesis of heavy elements occurs in the neutrino-driven winds of supernovae, it starts with free nucleons. Its outcome then depends strongly on bottlenecks in the reaction flow near the A=5 and A=8 gaps where there are no stable nuclei. Several poorly-measured or unmeasured cross sections between A=7 and A=12 could be important, with the reaction $\alpha + \alpha + n \rightarrow {}^{9}\mathrm{Be} + \gamma$ leading the list.

Element Production

Element production occurs differently in different stars. We outline here the production that occurs along the r-process path (either in core collapse supernovae or neutron star mergers), those that occur in novae, and those that occur in X-ray bursts. Nuclei play a role in each arena. For novae, stable beam structure measurements were recently performed to understand the $^{30}\mathrm{P}(p,\gamma)^{31}\mathrm{S}$ reaction which is a gateway to production of mass 30-40 isotopes in novae. These measurements were performed at ATLAS Gammasphere with fusion-evaporation techniques. HRIBF also measured $^{32}\mathrm{S}(p,d)^{31}\mathrm{S}$. Astrophysical simulations using nuclear structure information suggested a Sn-Sb-Te cycle that is closed by (γ,α) reactions would prevent formation of heavier elements by the rp-process. First experiments in this region to help better understand this suggestion were recently performed at HRIBF and probed ^{105}Te super-allowed α-decay and the ^{105}Sb separation energy. Many such examples of the relevance of nuclear physics experiments to astrophysical understanding exist.

Finally, we mention rp-process measurements of ^{32}Cl(p,γ)^{33}Ar which is believed to be a bottleneck for the process. The experiment identified the position of the relevant levels to 5 keV accuracy. Theory gave the proton decay width from spectroscopic factors, the gamma-decay width, and properties of the low-lying excited state in ^{32}Cl that gives rise to the stellar enhancement factor. Through a combination of new experiments and theory, the reaction rate uncertainty was reduced from a factor of 50 or more to just a factor of 3 for a wide range of temperatures (see Fig. 1).

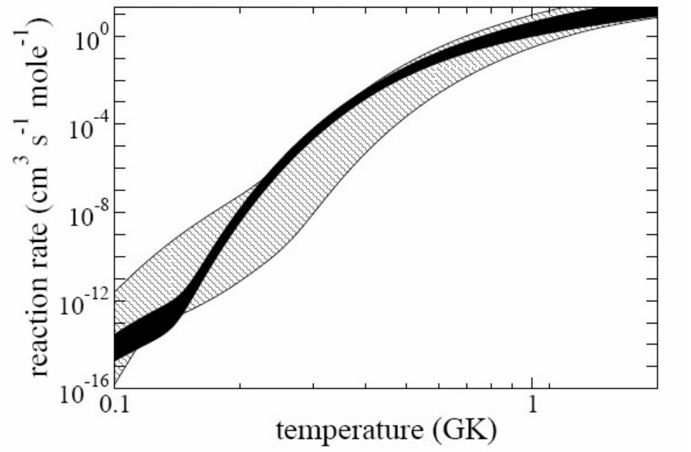

Figure 1. The reaction rate as a function of temperature for the reaction ^{32}Cl(p,γ)^{33}Ar. Shaded: previous results. Black: new results. (Courtesy of H. Schatz)

Numerous nuclear properties impinge on our understanding of astrophysical processes responsible for heavy element production. These same properties are of fundamental interest for understanding nuclei. A key role for experimental programs is to confront theoretical models of the nucleus with reality. For example, one of the key nuclear physics questions concerns whether the same shell gaps exist in very neutron-rich nuclei as their more stable. Does the shell structure change from a standard nuclear spin-orbit picture to a more reduced spin-orbit picture in very neutron rich nuclei? We do not know the experimental answer to this question, although there are hints from light nuclei that shell structure does indeed change from our standard picture in neutron rich nuclei. Such changes impact how nucleosynthesis processes actually occur in a neutron rich environment: weak shell closures would produce more abundant material near these closures. Thus, an experimental program to measure the shell closures and single particle energies near those closures – through knockout and transfer reactions and more indirect indications from beta decay – is very important to clarify both our understanding of nuclear properties and nucleosynthesis. Progress on the experimental side is being made today and will continue during the coming decade. For example, first measurements using the (d,p) technique on r-process nuclei at N=50 [^{82}Ge, ^{84}Se] and N=82 [^{130}Sn, ^{132}Sn, ^{134}Te] were carried out at HRIBF. NSCL measured the half-life of ^{78}Ni, and ISOLDE measured ^{126,128,130}Cd properties.

The mechanism by which the heaviest elements are produced has been understood since the late 1950s, but the details of the astrophysical site remain a mystery. The heaviest elements are made by the r-process, or the rapid neutron capture process of element synthesis. Once neutrons are present in sufficient quantities in a relatively hot environment (temperatures of one to three hundred keV) then they can easily capture on seed nuclei, such as iron, to build up new nuclei up to and including the uranium. The challenge is to find an astrophysical environment, in which neutrons are naturally present in large quantities.

The candidate environments are core collapse supernovae, gamma ray bursts, neutron star mergers, and a number of other possibilities. Core collapse supernovae, gamma ray bursts and neutron star mergers also release large quantities of neutrinos. At the places within these environments where the r-process is thought to occur, the neutrino emission is so strong that the neutrinos, through the charged current interactions, either contribute to or are responsible for the relative numbers of neutrons and protons, thus determining the prospects for making the heaviest elements. Furthermore, neutrino interactions on nuclei can influence the final abundance pattern from these nuclei. As a result, the neutrino physics, nuclear structure physics, and astrophysics are inextricably interwoven.

There have been a number of recent achievements in this area that promise a future understanding of this problem. New halo star data shows that the heavier r-process elements occur in a reliable and consistent pattern across a number of stars, while the light elements do not. This has lead to speculation that the r-process occurs in two sites or at least in two different types of conditions, and that furthermore fission cycling is responsible for one of these. The conditions under which fission cycling operate are even more restrictive however. Even more neutron richness of the material is required, at a level which far exceeds that which is currently predicted by astrophysical models. Preliminary studies of the effects of a sterile neutrino, which are much discussed in the neutrino community, have been shown to produce the requisite conditions. Further study is necessary however, to rule out other possibilities and to further elucidate the behavior of these new neutrinos.

Another recent achievement involves the first calculations of elements that are produced in gamma ray bursts. It has been shown that this nucleosynthesis is again linked to the neutrinos, and that an r-process can occur here as well. However, the conditions necessary for fission cycling have not been found, and so if this environment does indeed produce a significant fraction of the heavy elements, it would be the lighter r-process elements. These calculations only map out the available parameter space, further theoretical work must be done to explore this environment in detail, and to compare with the prospects at other potential sites such as neutron star mergers.

Finally, future measurements of nuclear masses, beta decay rates, neutron capture rates and neutrino-nucleus scattering cross sections are very important. Data in all these forms is required for predicting a final abundance pattern. Without this data, one cannot fully predict an abundance pattern and the effort to find an appropriate site is impeded. For example, neutrino-induced particle spallation has been speculated to alter the abundance pattern at the late stages of r-process formation. The extent to which this can occur depends on our understanding of the physical conditions, but also on our knowledge of the cross sections. Little data exists on these cross sections, and measurements are needed. Along similar lines, neutron capture on elements closer to stability such as those on the N=80 peak can effect global change to the r-process abundance pattern as the material freezes out of (n, γ),(γ, n) equilibrium and path passes to stability. While the material is still in equilibrium, nuclear masses and beta decay rates determine the path (in neutron number, proton number space) that nuclei follow. These effects all demonstrate the importance of the nuclear structure data in gaining a true understanding of the r-process.

Core Collapse Supernovae

Recent improvements in our understanding of the structure and thermal behavior of intermediate mass nuclei (A=50-100), enabled by our improving computational prowess, has driven a reassessment of the role that electron and neutrino capture reactions on such nuclei play during the collapse of the core of a massive star, the harbinger of a core collapse supernova. Bethe and his collaborators had shown that the low entropy of the iron core, and resulting small concentration of free nucleons, allows electron capture on A=50-60 nuclei, via Gamow-Teller (GT) transitions changing protons in the $1f_{7/2}$ level into neutrons in the $1f_{5/2}$ level, to dominate the deleptonization of the core prior to collapse. During collapse, increasing densities cause the characteristic nuclei in the core to increase in mass. Fuller realized that electron capture on heavy nuclei would soon be quenched in this picture as neutron numbers approach 40, filling the neutron $1f_{5/2}$ level. Independent particle model (IPM) calculations showed that neither thermal excitations nor forbidden transitions substantially alleviated this blocking, leading to the belief that electron capture on protons dominated that on heavy nuclei during core collapse.

Recent supernova models, using rates derived from a combination of Shell Model Monte Carlo and RPA (LMSH) have revealed that the domination by electron capture on heavy nuclei continues throughout collapse, until neutrino blocking and captures effectively stop deleptonization at densities of a few 10^{12} g cm^{-3} (A=100+). Figure 2 shows an example of the nuclear landscape under such conditions, with a wide range of nuclei from A=70-110 contributing, ranging from 0-6 neutrons from stability. The effect of the continued electron capture can be seen in Figure 3, which compares core collapse simulations using the old IPM rates (green) with those using the LMSH rates (red) [4]. As a result of increased deleptonization resulting from the LMSH rates, the supernova shock forms 0.1 solar mass deeper in the supernova. Parameterized studies, the dashed lines in Fig. 3, reveal that this is a systematic trend, with 10x variations in the rates producing approximately 0.1 solar mass adjustments in the location of the shock's launch.

The large number of nuclei that may participate in the deleptonization, and their neutron-richness, indicates that theoretical rates will be the mainstay of studies to improve our understanding of the role these reactions play and studies using a wide range of approaches are warranted. To test the currently available rates, and differentiate between alternatives as they are developed, experiments will be invaluable. Charge Exchange measurements, with RIBs for the unstable species, can tell us much about the strength and distribution of the Gamow-Teller resonances in such nuclei. Direct measurements of neutrino capture cross-sections for a selection of stable nuclei would be complimentary, providing insight into the translation of GT strength into weak reaction rates as well a measuring the forbidden contribution to such rates. Finally, understanding the role of nuclear electron capture in core collapse supernovae requires continued development of supernova modeling in order to explore the interplay between the deleptonization driven by electron capture and the myriad of other actors in this neutrino radiation, magnetohydrodynamic problem.

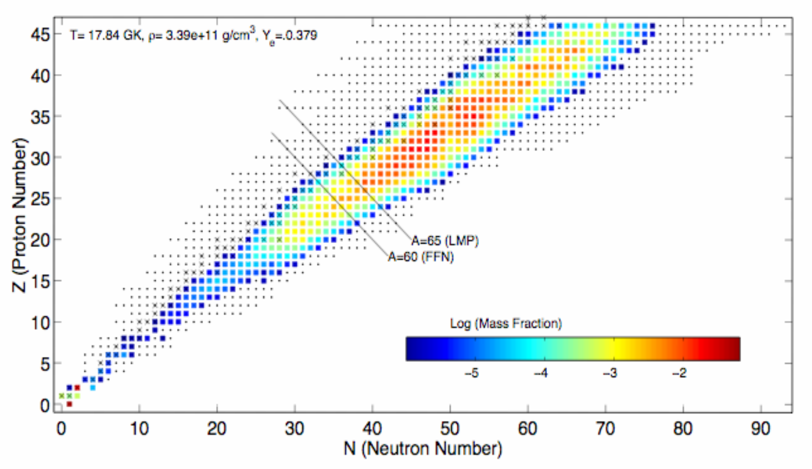

Figure 2. Sample of mass fractions of heavy nuclei during core collapse.
X denotes stable species. (Courtesy of R. Hix)

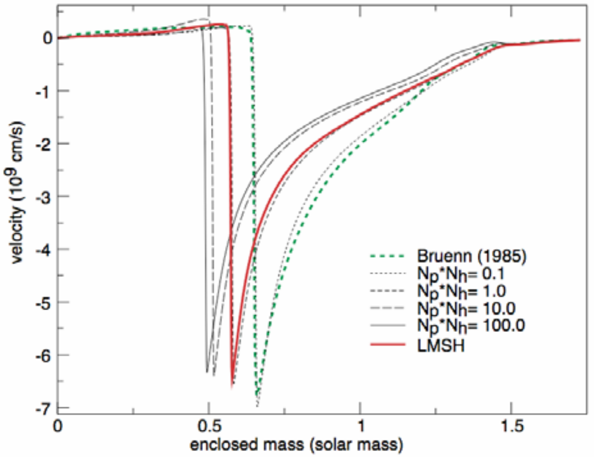

Figure 3. Impact of variations in nuclear electron capture
on the initial position of the supernova shock. (Courtesy of R. Hix)

The Nuclear Equation of State

Arguably the most uncertain part of the equation of state of infinite homogeneous nucleonic matter is the symmetry energy, a function which determines how the equation of state varies with the isospin-asymmetry. While experimental information from nuclear masses and resonances places the value of the symmetry energy at the nuclear saturation density between about 30 and 35 MeV, the exact value and the density dependence away from saturation density is uncertain. At the same time, the symmetry energy is an important input for the understanding of the isospin-independent part of the equation of state, the structure of nuclei, nuclear collisions, and many astrophysical processes.

Nuclear structure and nuclear matter: The symmetry energy is closely connected to the masses and relative sizes of neutron and proton radii in highly isospin-asymmetric nuclei. Recent work has shown that the neutron radius of neutron-rich nuclei is tightly correlated to the magnitude of the symmetry energy at about two-thirds saturation density. A relatively precise measurement of the neutron skin in lead which doesn't suffer from systematic uncertainties, PREX, will be performed at JLab in 2008. In isospin-symmetric nuclear matter, the symmetry energy is also an important factor when determining the compressibility modulus: it has been shown that varying the density dependence of the symmetry energy can affect the extraction of the compressibility from the experimental data on giant resonances. The sub-saturation density behavior of the symmetry energy is an active area of experimental and theoretical work, because the (i) equation of state at lower densities is not affected by three- and higher-body interactions and (ii) the neutron-neutron interaction is nearly at the so-called ``unitarity'' limit, where the properties of interacting fermions become universal.

Astrophysical processes: Neutron star cooling is sensitive to the symmetry energy because it determines whether or not the direct Urca cooling process (neutron beta-decay and its isospin analog), which cannot proceed unless the proton-to-neutron ratio is sufficiently large, will be allowed. Neutron stars with large symmetry energy and thus a large number of protons will be colder because of the presence of the direct Urca process in their cores. While isolated neutron stars are not cold enough to conclusively require the direct Urca process, recent data obtained on the cooling of neutron stars in low-mass X-ray binary systems is sufficiently rapid to suggest that some extra cooling mechanism (possibly from the direct Urca process) is playing a role.

Neutron star radii are also particularly sensitive to the symmetry energy at densities just above the saturation density. Neutron star radius measurements are improving, and a radius measurement with an uncertainty of half a kilometer provides a novel constraint on the symmetry energy at the relevant densities if the measurement is accompanied by some information on the neutron star's mass.

Finally, the neutrino spectra from supernovae and proto-neutron stars are also sensitive to the symmetry energy since the neutron-to-proton ratio dictates the ratio between, for example, the number of electron neutrinos to anti-neutrinos.

Heavy-ion collisions: The dynamics of intermediate-energy heavy-ion collisions is strongly affected by the symmetry energy as evidenced in the recent work on how the symmetry energy is related to isospin diffusion, fragment distributions, flow, and particle ratios. The determination of the symmetry energy at both sub-saturation and super-saturation densities is a prime motivation for much of the experimental work in this area.

Nuclear Astrophysics: A Multi-Disciplinary Challenge

Advancing our knowledge of nuclear astrophysics requires the coordinated efforts of nuclear experiments, nuclear theory, and astrophysics theory. By its nature, nuclear astrophysics can only proceed with a multi-disciplinary effort. Prioritization of nuclear experiments can only come from an understanding of the astrophysics of each nucleosynthesis site, while the astrophysical modeling is only as accurate as the nuclear data on which it is based (see Figure 4). Theory of nuclear structure and reactions serves as the glue, providing estimates for the many unmeasured reaction rates, and translating laboratory measurements into nuclear structure information and ultimately thermonuclear reaction rates. The coordination between these fields is often passive, with the communities exchanging information only through the literature. However a multitude of recent efforts, both large scale (e.g. the Joint Institute for Nuclear Astrophysics and the Terascale Supernova Initiative, SciDAC-I Center for Supernova Research and the SciDAC-II effort ‘When Good Stars go Bang’) and more individual scale have demonstrated the great benefits of active collaboration among the disciplines. Such interdisciplinary efforts should be strengthened to speed up progress on studies of a wide range of astrophysical phenomena. One area that holds tremendous multi-disciplinary opportunity in the next five years is to forge the theoretical connection between laboratory measurements of transfer, Trojan horse, and other surrogate reactions and the rates of crucial thermonuclear reactions that occur in supernovae. These indirect techniques have long been touted as a means of laying an empirical foundation for the rapid neutron capture process -- which produces more than half of the elements heavier than iron. Advances in observations have now shown that the surfaces of some very old, very metal poor stars in the halo of our Galaxy have an abundance

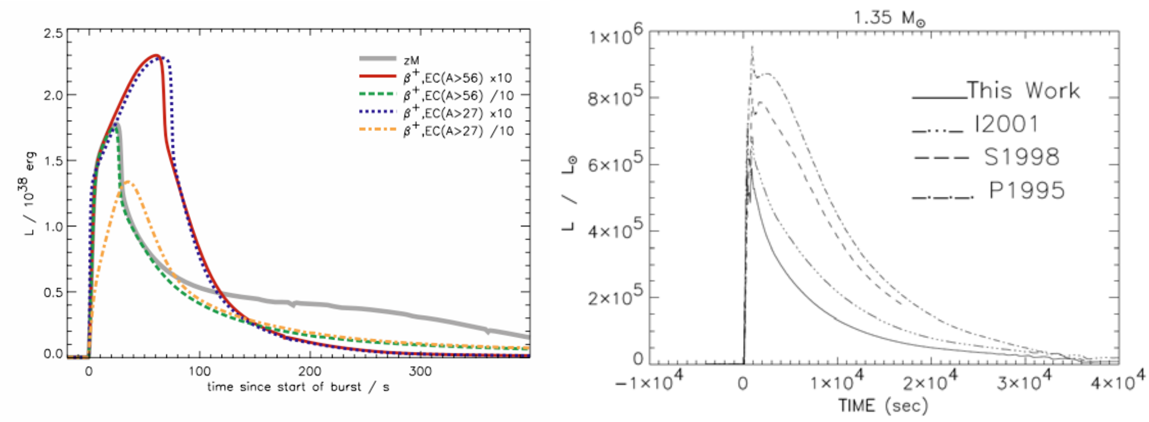

Figure 4. The impact of thermonuclear reaction rate variations on the light curves of Novae (right, courtesy of W. R. Hix and S. Starrfield) and X-ray bursts (left, from S. Woosley *et al.*, Ap. J. Suppl. **151**, 75 (2004)).

pattern that mirrors that of the r-process pattern in the solar system. Simultaneously, laboratory measurements of important reactions are now being made with neutron-rich unstable beams. However, the theory to translate this into improvements in nuclear structure and reaction models is not yet in place. To take full advantage of capability of current and future radioactive beam facilities, advances in this critical area are needed.

Another area with rich possibility for the combination of nuclear experiment and nuclear theory to impact nuclear astrophysics is by developing a comprehensive understanding of nuclear structure near the drip lines. Even with the radioactive beam facilities now on the drawing boards, the masses, decay lifetimes and other properties of many nuclei of interest for the r and rp-process will require theoretical understanding, potentially including fission barriers and fragment sizes for the neutron-rich nuclei. Without such an understanding, our ability to use astronomical observation to constrain astrophysical scenarios is limited

Nuclear Science and Astrophysics at the National Ignition Facility

The National Ignition Facility (NIF), the latest and largest fusion laser in the world, will be completed in 2009 and ignition-capable in 2010. Preliminary experiments will begin in 2008. Comprised of 192 beams, it will focus 1.8 megajoules (MJ) of blue light (3w, 351 nm) into specialized target assemblies, to compress and ignite deuterium-tritium (DT) fuel to densities and temperatures an order of magnitude higher than the Sun's burning core. Constructed by the National Nuclear Security Administration (NNSA) at Lawrence Livermore National Laboratory (LLNL), it will provide basic and applied scientific support for missions across all of DOE and other federal agencies. It is anticipated that roughly 15% of the NIF program will be devoted to basic science benefiting the DOE Office of Science and the National Science Foundation.

There is a long tradition of well-controlled and reproducible laboratory astrophysics measurements being carried out at fusion-class lasers without ignition, i.e. studies of atomic opacities, equation-of-state, and radiative hydrodynamics. However, for the first time since the invention of the Inertial Confinement Fusion (ICF) concept in 1960, NIF will produce thermonuclear burn, opening up remarkable new opportunities specifically for the study of unique astrophysically-relevant nuclear reactions. A standard ignition shot will release 20 MJ of energy, or 10^{19} fusion neutrons (14 MeV) in 10-20 picoseconds, from a 25-micron-radius volume. The resulting neutron flux is prodigious, ~ 10^{34} cm^{-2} s^{-1}. Furthermore, specially designed capsules offer the possibility of changing the burn time and neutron yield over a wide range to accommodate different scientific programs.

Target nuclei of interest, either stable or unstable, may be loaded into the target along with the DT fuel up to several parts in 10^4. Post-ignition radiochemical analysis accompanied by x-ray and neutron diagnostics will enable accurate cross sections to be measured for low-yield exotic reactions. Studies are underway to evaluate potential experiments, for processes such as multiple neutron reactions to probe reactions on short-lived ($10^{-(15-12)}$ s) highly excited states; very low-energy charged particle reactions needed for the solar model, and studies of atomic screening in sub-Coulomb barrier reactions. The scientific possibilities afforded by such an extreme stellar-like environment may ultimately be limited only by the imagination.

VI. Nuclear Matter Equation of State in the Laboratory and in Astrophysics

(Conveners: Jorge Piekarewicz, Sanjay Reddy, and Betty Tsang)

Compelling Scientific Questions

Understanding the equation of state (EOS) of nuclear matter is a central goal of nuclear physics that cuts across a variety of disciplines. Indeed, the limits of nuclear existence, the dynamics of heavy-ion collisions, the structure of neutron stars, and the dynamics of core-collapse supernova, all depend critically on the equation of state of hadronic matter. While remarkable advances in both terrestrial experiments and space observations have started to reshape the field, the promise of new *facilities for the future of science* will guarantee continuing discoveries for many years to come. Figuring prominently among these, is a *"Facility for Rare-isotope Beams"* (FRIB) that by creating a detailed map of the nuclear landscape, will constrain the EOS at large neutron-proton asymmetries. Further, the commissioning of space telescopes and land-based observatories operating at a variety of wavelengths, promises to turn the study of neutron stars from theoretical speculation into powerful diagnostic tools of the equation of state. Finally, new gravitational wave detectors probe the fundamental nature of space-time and the nature of the most violent events in the Universe. Gravitational waves are emitted by the acceleration of astronomical masses, often in response to the enormous pressures produced by dense baryonic matter.

A neutron star is a gold mine for the study of the phase diagram of cold baryonic matter (see Fig. 1 for an accurate rendition of the expected structure of a neutron star). Indeed, the only input that spherically symmetric neutron stars in hydrostatic equilibrium are sensitive to is the equation of state of neutron-rich matter. So with this focus in mind, we pose the following set of compelling scientific questions for the next decade. While succinct and of an astrophysical flavor, answering these questions will require a concerted and sustained effort from laboratory experiments, astronomical observations, and theoretical analyzes.

- *What is the maximum mass of a neutron star?*
- *What is the radius of a neutron star of a given mass?*
- *What is the physical origin of transient phenomena in neutron stars?*

The maximum mass of a neutron star, a limit of purely general relativistic origin, is of fundamental importance to both stellar evolution and black-hole searches. Moreover, such a determination would establish the highest energy density of observable cold baryonic matter. The limiting mass of a neutron star is particularly sensitive to the high-density component of the equation of state and, consequently, poorly constrained by laboratory experiments. Thus, the most stringent limits on the maximum mass of a neutron star must come from astronomical observations. Observations of a significant large mass (of about 2 solar masses) could exclude certain classes of equations of state. Further, it will help elucidate the role of non-nucleonic degrees of freedom and will test the predictions of QCD at high densities. *During the next Long-Range-Plan (LRP) period, we will have the opportunity to determine the limiting mass of a neutron star and to significantly constrain the phases of cold dense matter.*

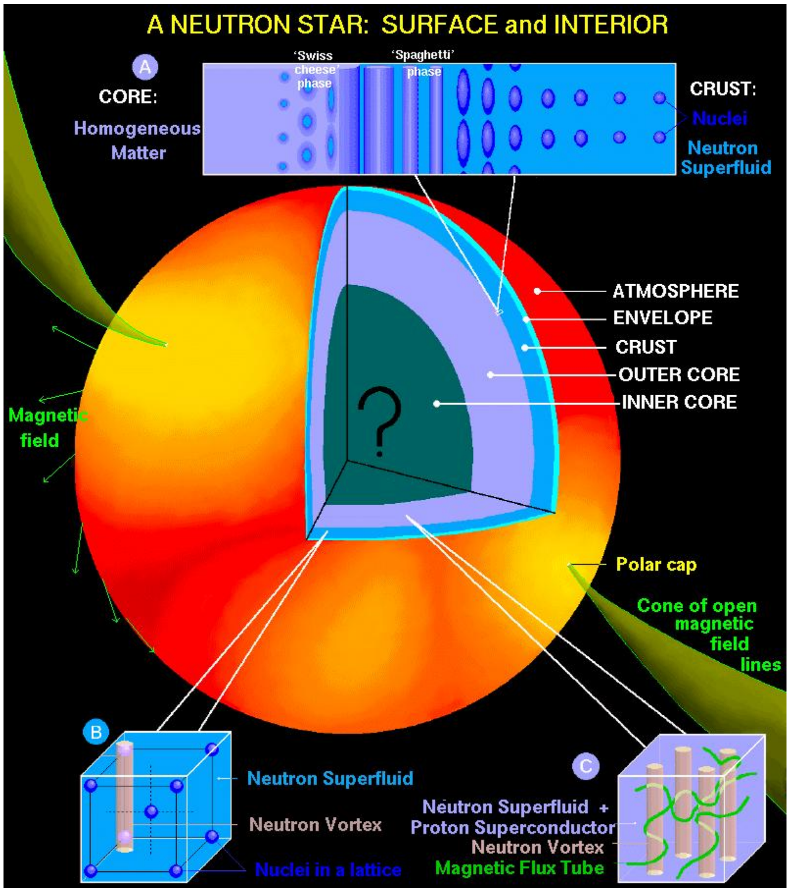

Figure 1. Accurate rendition of the structure and phases of a neutron star
(courtesy of Danny Page).

It is an extrapolation of 18 orders of magnitude from the neutron radius of a heavy nucleus to the approximately 10 km radius of a neutron star. Remarkably, both the neutron radius of a heavy nucleus and the radius of a neutron star depend critically on the pressure of neutron-rich matter. Such correlation among objects of such a disparate size is not difficult to understand. Heavy nuclei develop a neutron-rich skin as a result of both a large neutron excess and a Coulomb barrier that reduces the proton density at the surface of the nucleus. Thus, the thickness of the neutron skin depends critically on the pressure exerted on the outer neutrons. It is this same pressure that supports a neutron star against gravitational collapse. The pressure of neutron-rich matter is intimately related to the density dependence of the symmetry energy. The symmetry energy quantifies the penalty imposed on the system due to departures from the symmetric limit of equal number of neutrons and protons. As such, it is poorly constrained by existing ground-state properties of stable nuclei. *During the next LRP period, we will have the opportunity to determine the neutron radius of a heavy nucleus and the radius of a neutron star through a concerted effort of laboratory experiments on exotic nuclei and astronomical observations.*

Transient phenomena, such as X-ray bursts, super-bursts and giant-flares, are some of the most spectacular and energetic phenomena associated with neutron stars. These phenomena provide a powerful observational tool to probe the underlying nuclear physics that controls nuclear reaction rates, weak interactions in nuclei and nuclear matter, and the equation of state of dense baryonic matter. X-ray bursts are powered by nuclear burning of H/He in accreting neutron stars, while super-bursts are expected to arise due to the ignition of carbon in a deeper layer (*"heavy-element ocean"*) of the star. Highly magnetized neutron stars (*"Magnetars"*) exhibit frequent flares that are suspected to be powered by the energy released as the enormous magnetic field in the solid crust of the neutron star relaxes over time. *During the next LRP period, we will have the opportunity to develop quantitative models of these phenomena with the appropriate nuclear physics that will, in turn, provide a means to measure the mass and radius of neutron stars and could potentially aid in the determination of the composition, phase structure, and superfluid properties of matter in the crust of neutron stars.*

Major Accomplishments since the Last Long-Range Plan

During the last long-range plan period extraordinary progress was made in answering some key questions pertaining to the nuclear-matter EOS. The following list - which is by no means exhaustive - provides a representative set of some of the major achievements in this area.

- *The ground-state of cold baryonic matter at ultra-high densities has been shown from first-principles QCD to be a color superconductor in a color-flavor-locked (CFL) phase.*
- *The pressure of (hot) symmetric nuclear matter up to densities as high as four times nuclear-matter saturation density has been measured in laboratory experiments. A pressure of the order of P 10^{29} atm at the highest density represents the highest pressure ever recorder in terrestrial experiments.*
- *Robust correlations have been established between the neutron-skin of heavy nuclei, the density dependence of the symmetry energy, heavy-ion observables, and a myriad of neutron-star observables.*
- *Reliable extractions of neutron-star radii have started to emerge.*
- *Neutron stars with masses larger than the "canonical" value of 1.4 solar masses have been observed.*

A commonly conjectured phase diagram for hadronic matter is displayed in Fig. 2. For cold catalyzed matter two regions of the phase diagram are fairly well understood. One of these regions corresponds to symmetric nuclear matter in the vicinity of the equilibrium density, a region that has been constrained by the wealth of existing ground-state data on stable nuclei. The other region that has been constrained - exclusively by theoretical means - is the ultra-high density region. At these densities the baryons have *"melted"* and the ground state of cold dense matter has evolved into a color superconductor with quarks paired in a color-flavor locked (CFL) pattern.

Energetic nuclear collisions provide the only available means to compress nuclear matter to several times its equilibrium density under laboratory conditions. An observable particularly sensitive to the EOS is the flow of particles in a direction perpendicular to the incoming beam.

Energetic collisions of two gold nuclei have been used to constrain the EOS of symmetric matter for densities up to and above 4 times nuclear-matter saturation density. At the highest density, pressures as large as 10^{29} atm were extracted, representing the highest ever recorder pressure in the laboratory. As indicated in Fig. 3, such analyzes place important constraints on theoretical models of the equation of state.

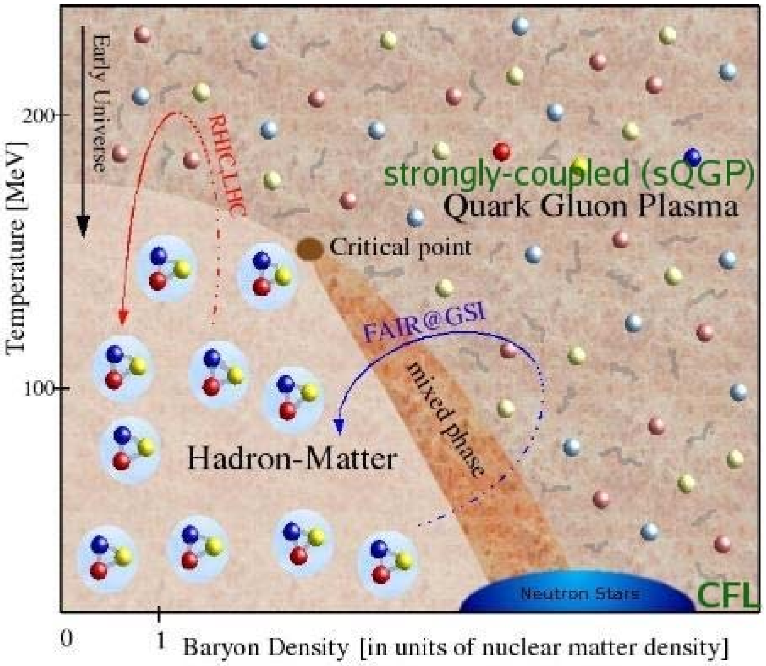

Figure 2. A conjecture phase diagram of baryonic matter.

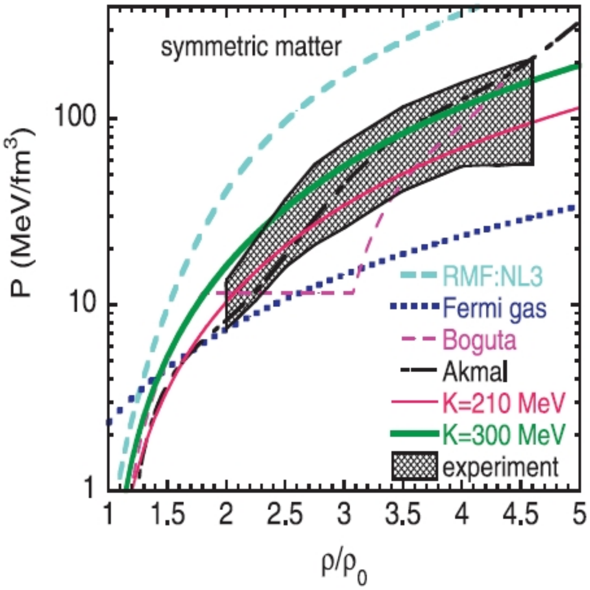

Figure 3. Laboratory constraints on the nuclear-matter equation of state (from P. Danielewicz *et al.*, Science **298**, 1592 (2002)).

During the past several years sensitive correlations between the neutron radius of a heavy nucleus and several neutron-star observables have been established from a purely theoretical basis. As the same pressure that supports a neutron star against gravitational collapse creates a neutron skin in a heavy nucleus, an intriguing correlation was established: the thicker the neutron skin of a heavy nucleus, the larger the radius of a neutron star. Additional correlations have emerged between the neutron skin of a heavy nucleus and various neutron star observables, such as stellar moments of inertia, crustal vibration frequencies, and cooling rates.

The past decade has seen the first determination of neutron-star radii from observations of neutron stars in quiescent X-ray binaries within globular clusters. While at present only the *“radiation radius"* has been determined - a quantity that depends on both the intrinsic radius and the mass of the neutron star - significant constrains have already been imposed on the equation of state (see Fig. 4). In particular, if the upcoming measurement of the neutron radius of a heavy nucleus is measured to be relatively large while that of a neutron star relatively small, this may be indicative of a phase transition to quark matter.

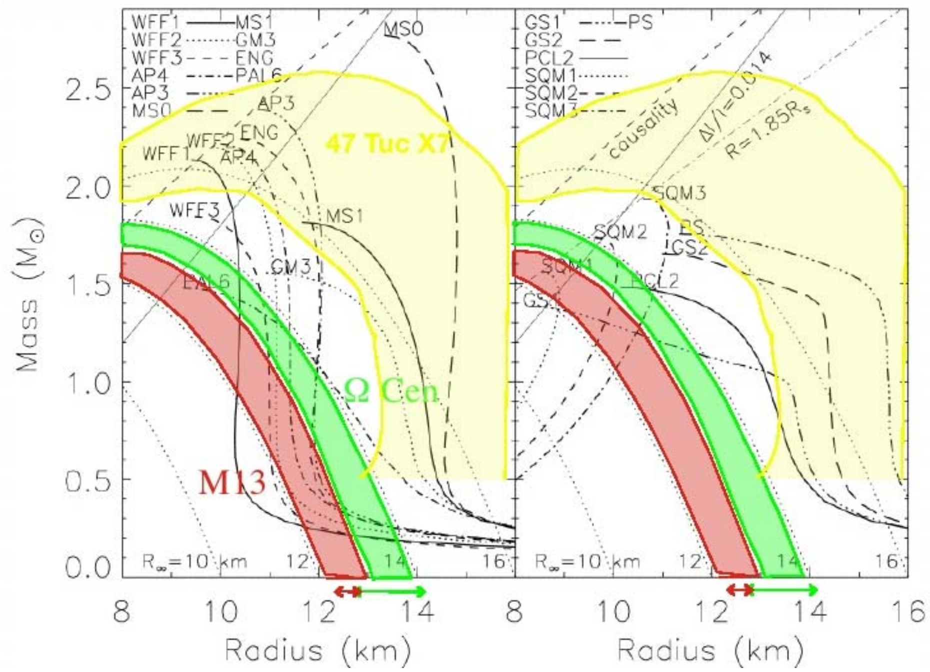

Figure 4. Observational constraints on the nuclear-matter equation of state
(from B. Rutledge’s presentation at the Town meeting).

Neutron-star masses extracted from several neutron-star binaries have been measured with unprecedented accuracy (see Fig. 5). Remarkably, all masses fall within a very narrow window in the vicinity of 1.4 solar masses. A more promising system for finding massive neutron stars is a neutron star accreting mass from a white-dwarf companion. Indeed, a particularly interesting case is that of PSRJ0751+1807, a neutron star with an estimated mass of 2.1±0.2 solar masses making it the most massive neutron star ever measured, thereby placing stringent constraints on theoretical model of the EOS (see Figs. 4 and 5).

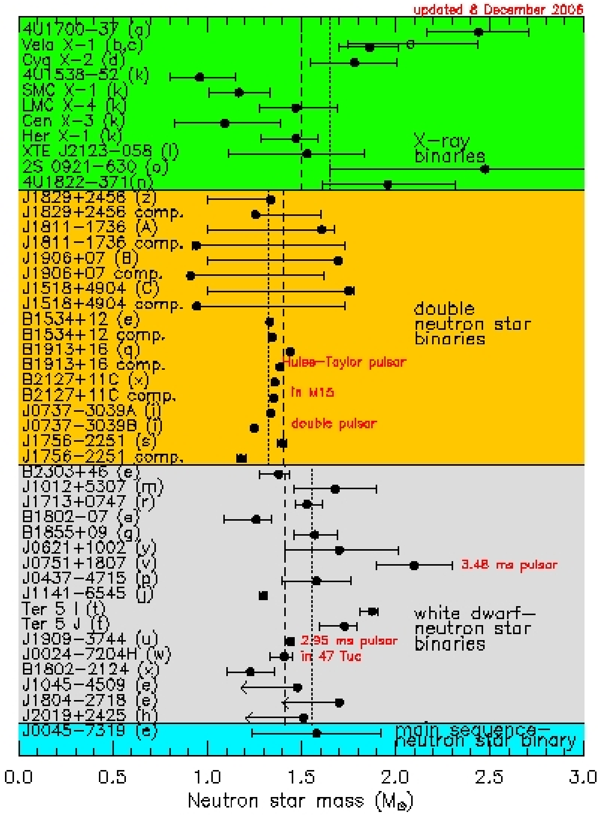

Figure 5. Masses of neutron stars in radio binary pulsars and in X-ray binaries (from J. Lattimer's presentation at the Town meeting).

Facilities and Resources

Progress in the understanding of the equation of state of neutron-rich matter has been hindered by our reliance on experiments with stable nuclei. During the next LRP, the advent of new experimental and observational facilities will drastically reshape our understanding of the EOS. The following (short) list provides a representative set of major facilities, experiments, and astronomical observations that will be required to advance the field.

- *The Parity Radius Experiment at the Thomas Jefferson National Accelerator Facility*
- *A High-Energy Facility for Rare-Isotope Beams (FRIB.*
- *Radio and X-Ray Telescopes of Increased Sensitivity*
- *Advanced Gravitational Wave Detectors*

The *Parity Radius Experiment* (PREX) at the Jefferson Laboratory aims to measure the neutron radius of ^{208}Pb via parity violating electron scattering. In contrast to all previous hadronic experiments that suffer from controversial uncertainties, this purely electroweak measurement promises to be both accurate and model independent. Parity violating electron scattering is particularly sensitive to the neutron density because the neutral weak vector boson (Z^0) couples preferentially to the neutrons. Thus, through an accurate determination of the thickness of the neutron skin of a heavy nucleus, PREX will provide a unique experimental constraint on the density dependence of the symmetry energy.

Since the last LRP significant progress has been made in identifying various experimental probes that are sensitive to the density dependence of the symmetry energy. These probes include isoscaling, isospin diffusion, neutron-to-proton as well as π^+-to-π^- ratios and flow. As the sensitivity of these probes increases with the asymmetry between the beam and the target, the next generation of experiments should utilize radioactive beams of extreme isospin composition. In particular, the study of pion and kaon production in nucleus-nucleus collisions will yield meaningful constraints on the high-density component of the symmetry energy. A time projection chamber (TPC) has been identified to be most suited to study pions and other light isotopes produced in collisions involving high energy radioactive beams. Thus, the proposed FRIB should produce beams with an energy between 30 to 200 MeV per nucleon, with an upgradable option to even higher incident energies.

In 1990 two of the most important X-ray missions were lunched within months of each other. The *Chandra* and *XMM/Newton* missions have brought true spectroscopic capabilities into X-ray astronomy for the very first time. Observations of neutron stars in quiescent X-ray binaries within globular clusters offer the best hope towards an accurate determination of *"Mass-Radius"* relationships for neutron stars. These observations are providing new probes of neutron star structure, but precise characterization of the properties of neutron stars is not yet within reach. And while both (Chandra and XMM/Newton) missions could operate past 2010, significant advances in observing capabilities are required to fully exploit these sensitive probes. The Constellation-X mission (with an optimistic lunch date of 2016) will provide the high spectral resolution and large collecting area required to make simultaneous Mass-Radius measurements of neutron stars with an expected 5% accuracy. The nuclear-physics community must understand that while not directly responsible for the success of these missions, our unwavering support is vital for the survival of this newly established partnership.

The next LRP is expected to witness the historical detection of gravitational waves. Coalescing neutron stars are among the most important sources of gravitational waves and theoretical advances suggest how to constrain the nuclear equation of state using gravitational-wave signals. Indeed, the latest simulations for the merger of binary neutron stars show that a "hyper-massive" neutron star forms after the merger if the total mass is smaller than a threshold value that depends critically on the equation of state. Moreover, at the end of the inspiral phase, the gravitational waveforms change and the transitional frequency depends sensitively on the radius of the neutron stars. Finally, the gravitational wave signal may be qualitatively different if the objects are made of self-bound strange quark matter, thereby placing strong constraints on the possible phases of dense nuclear matter.

Scientific Impact on/from Other Fields

Understanding the equation of state of nucleonic matter, namely, the dependence of the energy of the system on density, temperature, and isospin asymmetry, is a complex quantum many-body problem with a close relationship to several field of physics. The following list provides a representative set of interdisciplinary connections:

- *Fermionic superfluidity with unbalanced spin populations.*
- *Atomic "engineering" of exotic quantum phases.*
- *Universal aspects of Coulomb frustrated systems.*

The ground state of cold baryonic matter at *"ultra-high"* densities has been shown to be a color superconductor. Given that at these asymptotic densities the mass of the strange quark is negligible as compared to its Fermi momentum, the ground state consists of an equal (neutral) mixture of up, down, and strange quarks, in a color-flavor-locked (CFL) pairing pattern. And while the CFL phase is favored in the limit of infinite density, the nature of the pairing pattern at the densities present in the core of neutron stars (where the mass of the strange quark can no longer be neglected) is a vigorously debated question. Specifically, one would like to understand the emerging pairing pattern for fermionic species with *unbalanced* populations. Due to the pristine and controlled environment of *ultracold atoms*, answers are starting to emerge. Recent experiments using an ultracold mixture of fermionic lithium-6 atoms seem to suggest that the conventional superfluid can tolerate a mismatch of up to 10% of unpaired fermions.

The nucleon-nucleon system in the isovector channel displays an anomalously large (and negative) s-wave scattering length, suggesting that the formation of a bound state just barely failed. It is then intriguing to investigate the equation of state of such a strongly-interacting fermionic system. Recent experiments with ultracold atomic Fermi gases have opened the possibility of investigating the crossover from a Bose-Einstein condensate (BEC) to a Bardeen-Cooper-Schrieffer (BCS) superfluid. Remarkably, in such systems the s-wave scattering length can be magnetically tuned. For positive values of the s-wave scattering length, atoms with different spins pair into bound molecules that Bose condense at low enough temperatures. This state may then be converted into an ultracold Fermi gas with a small negative scattering length. In this weak-pairing regime, BCS theory is applicable and the system is observed to become a superfluid. However, in the BEC-BCS crossover region the s-wave scattering length may be arbitrarily large and one enters into the novel strongly-correlated regime. In dilute systems with a very large scattering length but negligible effective range - the so-called unitarity limit where the system displays *Universal* behavior - significant progress has been made. Pure neutron matter, however, does not fall strictly within this domain as the effective range of the two-body interaction (of the order of 3 fm) is not particularly small. Yet, ultracold atoms allow a precise control of the experimental conditions. Thus, the creation under control laboratory conditions of an ultracold fermionic system with both a scattering length and an effective range comparable to those of the neutron-neutron system may soon become a reality.

Neutron-rich matter at densities below nuclear-matter saturation density exhibits rich and complex structures that emerge from a dynamical competition between short-range nuclear attraction and long-range Coulomb repulsion. At densities of 10^6 to 10^{11} g/cm^3 these length scales are well separated and the system organizes itself into a crystalline lattice of neutron-rich nuclei. In contrast, at densities of the order of half nuclear-matter saturation density uniformity in the system is restored. Yet the transition region from the highly-ordered crystal to the uniform Fermi liquid is complex and not well understood. Length scales that were well separated in both the crystalline and uniform phases are now comparable, giving rise to "*Coulomb frustration*". It has been speculated that the transition to the uniform phase goes through a series of changes in the dimensionality and topology of these complex structures known as "nuclear pasta". The connection to Condensed-Matter Physics could not be stronger. It has been shown that Coulomb-frustrated systems of lower dimensionality, such as the two-dimensional electron gas, are universally unstable to the formation of new intermediate phases in the transition region from a Wigner crystal to a uniform Fermi liquid. These intermediate phases known as *"microemulsion"*, are the two-dimensional analogs to the nuclear pasta. And while some tantalizing results are starting to emerge, no universal behavior is expected to occur in three dimensions.

Finally, the relation between nuclear physics and astrophysics has evolved from one of interdisciplinary character to a truly successful partnership. The coming decade will witness a vastly extended database of neutron stars that, when fully integrated with theoretical analyzes and laboratory experiments, will produce a giant leap in our understanding of the equation of state of baryonic matter. Advances made in neutron-star research, such as the determination of the maximum mass of a neutron star and mass-radius relationship, will support and complement laboratory experiments and theoretical investigations. Also during the next LRP, the historical detection of gravitational waves is expected. Gravitational waves in coalescing neutron stars detected during their final inspiraling phase will provide stringent constraints on the equation of state. Conversely, improved models of the EOS will guide neutron-star observations and will enable accurate predictions of gravitational-wave signals. Indeed, Mass-Radius relationships predicted with various models are commonly cited in X-ray observing proposals and guidance from the nuclear community motivates telescope-allocation committees to grant observation time. It is imperative that the nuclear-physics community keeps this successful partnership alive through a vibrant research program.

VII. Facilities and Instrumentation

(Conveners: Jim Beene, Jerry Nolen, I.-Yang Lee, and Michael Thoennessen)

Infrastructure and Resources in Nuclear Structure and Nuclear Astrophysics

Advances in accelerator facilities and instrumentation always lead to new discoveries in nuclear science. The construction of a facility for rare isotope beams (FRIB) will provide a tremendous discovery potential in nuclear structure, reaction and astrophysics. Although at a reduced cost of $550M, it will still be unmatched elsewhere when completed in 2017. Thus, the highest priority for major new construction in nuclear physics is the construction of FRIB. It is apparent that within this budget constraint it will be very difficult to build designated new equipment ready to be used at FRIB from the beginning. Thus it is absolutely essential to adequately fund continuous R&D, design, and construction of instrumentation at existing facilities that can be used once FRIB becomes operational.

The current stable and radioactive beam facilities with their state-of-the-art instruments have been very productive in the last 5 years. However, due to budget constraints, most of the facilities are not operating at full capability. Appropriate funds for operations and near-term upgrades of existing national and university laboratories are required to allow the effective utilization of these facilities.

1. National Laboratory and University Accelerator Facilities

The accelerator facilities located at national laboratories and universities are the backbone of the nuclear structure and nuclear astrophysics research in the U.S. The long-term goal of the field is a next generation facility for rare isotope research. It is crucial that the existing facilities remain competitive in preparation of this goal. R&D at these facilities concentrates on techniques, equipment, and instrumentation that can be used at FRIB. These facilities focus on many different aspects of research in nuclear structure and nuclear astrophysics and provide a broad and coherent program. This includes the low-energy nuclear astrophysics program which complements the FRIB efforts. The optimal utilization of these facilities is crucial for a healthy community of researchers and students that will be ready when FRIB comes online.

1.1. National Laboratory Based Facilities

ATLAS at ANL

ATLAS is a DOE National User Facility for the investigations of the structure and reactions of atomic nuclei. With high quality, high intensity beams of any element at energies comparable to internal energies of the nucleus, ATLAS is the ideal accelerator for the study of the structure of nuclei as an assembly of protons and neutrons.

ATLAS delivers with high reliability about 5500 hours per year of beams for research when running seven days per week, and, of these, about 1000 hours per year have been radioactive beams in recent years. The radioactive beams are used for both nuclear astrophysics and nuclear structure research. These radioactive beams are produced with two distinct approaches: the two-accelerator method and the in-flight technique, and the intensities of these beams are from about $10^4 s^{-1}$ to $6 \cdot 10^6 s^{-1}$ on target.

The suite of research instruments available at ATLAS enables a wide variety of nuclear science programs from stopped beam measurements with ion and atom traps, measurements of cross sections of reactions at energies relevant to nuclear astrophysics, and nuclear structure and reaction mechanism studies at energies at and well above the Coulomb barrier. The present instruments include: the Fragment Mass Analyzer (FMA) and associated detectors; Gammasphere, the national γ-ray facility, is currently located at ATLAS; two split-pole magnetic spectrographs and associated detectors used for astrophysics, AMS measurements, fusion reaction studies, and in the gas-filled mode for delivery of exotic isotopes to the gas catcher and atom traps; two Penning traps and associated rare isotope beam manipulation systems; an atom trap for studies such as the recent measurement of the charge radius of ^{6}He; and other general-purpose detectors and beam lines. This array of instruments is directly useful for stopped and reaccelerated beam research at a future US advanced exotic beam facility.

Upgrades to ATLAS that are currently in progress are a project to increase the energy by about 25%, the Californium Rare Isotope Breeder Upgrade (CARIBU), and the Helical Orbit Spectrometer (HELIOS) in addition to an RF beam sweeper to improve rare isotope beam purity. CARIBU comprises a 1-Ci ^{252}Cf source coupled with a gas catcher and charge breeder to provide unique beams of neutron-rich fission fragments with intensities up to $7 \cdot 10^5 s^{-1}$ for stopped and reaccelerated-beam research. HELIOS is a project being done in collaboration with Western Michigan University and is a large acceptance spectrometer for studying transfer reactions in inverse kinematics with radioactive beams.

There is also a plan for a further upgrade of ATLAS called Super CARIBU that will give about 10 times more beam intensity of radioactive fission-fragment stopped and reaccelerated exotic beams for the era leading towards the next generation exotic beam facilities. This project involves the construction of a high efficiency low-charge-state injector for ATLAS and an increase of spontaneous fission yields via the use of both a stronger ^{252}Cf source and a ^{254}Cf source.

The independently phased superconducting resonator technology developed at Argonne for ATLAS is the basis for both the high power heavy-ion driver and the post accelerator of rare isotopes at the future facility. Continuous development of this and related accelerator technologies and the associated instrumentation for fundamental investigations in nuclear science is essential to the national program leading to the greatly expanded capabilities of future projects. Scientists and engineers from several divisions at Argonne are actively pursuing the development of the technologies that form the underpinnings of future facilities. In the coming years ATLAS and its users must be adequately funded to continue to play a vital role in both the scientific and technological preparations for the next generation.

HRIBF at ORNL

The Holifield Radioactive Ion Beam Facility (HRIBF) was developed from an existing accelerator complex at Oak Ridge National Laboratory in the mid 1990s. Radioactive species are produced by intense light-ion beams from the Oak Ridge Isochronous Cyclotron and post-accelerated by the 25-MV tandem electrostatic accelerator. The radioactive-ion-beam injector system (IRIS1), links production and post-acceleration and consists of a high-voltage platform on which the production target and beam preparation and purification hardware reside, and a high-resolution Isobar Separator. The suite of radioactive ion beams (RIBs) available for research is expanding rapidly. More than 175 isotopes have been accelerated and approximately 30 additional species are available as low-energy (~50 keV) beams. More than 50 post-accelerated beams, including ^{132}Sn, have intensities of at least 10^6 s^{-1}. The tandem post accelerator delivers high-quality beams at continuously variable energies up to ~10 MeV/nucleon at A=40 and ~5 MeV/nucleon at A=130. The ability of HRIBF to deliver beams of reaccelerated beams of neutron-rich fission fragments at energies above the Coulomb barrier is currently unique. The research program includes studies of reactions relevant to explosive nucleosynthesis and solar physics, exploration of nuclear structure at the proton drip line and near doubly-magic ^{78}Ni and ^{132}Sn, central collision studies in very neutron rich systems clarifying the role of neutron excess for heavy element production, and surrogate reaction studies relevant to stockpile stewardship and nuclear astrophysics. Research equipment optimized for radioactive-ion-beam experiments is available, including two recoil separators, a gas-filled spectrograph, the CLARION γ-ray detector array, the HYBALL charged-particle detector array, silicon-strip arrays, specialized detectors and electronics for decay studies, and detectors to monitor and image low-intensity radioactive ion beams. Major equipment development now planned or underway includes a doubling of CLARION efficiency, a new low-energy beam facility, development of neutron detector arrays for βn studies, a high-density gas-jet target, a new-concept detector system for fusion-fission studies, and a large-scale silicon barrel array. Many existing and planned experimental tools can be used at the future FRIB.

A program is underway to substantially improve HRIBF performance. In 2005, the High Power Target Laboratory (HPTL) was completed, providing extensive ISOL production and beam purification and manipulation R&D capability. A second fully functional ISOL production station (IRIS2) is now being configured, using the shielded space and hardware developed for HPTL. IRIS2 will provide badly needed redundancy in critical ISOL hardware, along with more scope for advanced beam manipulation tools. After completion in early 2009, IRIS2 will substantially improve the operational efficiency of HRIBF, increasing the number of RIB hours available to researchers by ~50%. A plan has been developed to improve our RIB production capability by installing a turn-key electron accelerator capable of delivering a 100 kW electron beam, at an energy in the range of 25 to 50 MeV. This is the most cost-effective way to maintain leadership class capability in our neutron-rich beam program. With existing HRIBF target technology, and modest-sized targets, such a facility will be capable of generating 10^{13} photo-fissions per second. This is ~20 times larger than the current HRIBF proton-induced fission capability, but since photo-fission is a much “cooler” process the yields of the most neutron-rich species are much more strongly enhanced. As an example, the yields of ^{132,134,138}Sn yield will be ~300, 1000, and 12000 times larger than current capability respectively.

The 88-Inch Cyclotron, Lawrence Berkeley National Laboratory

The 88-Inch Cyclotron is a sector-focused, variable energy cyclotron with axial injection from any of three electron cyclotron resonance (ECR) ion sources. This versatile combination can accelerate high intensity light ion beams such as protons, deuterons and alphas up to 55 MeV, 65 MeV and 130 MeV, respectively. The maximum energy is 32 MeV/nucleon for beams up to Ar, 18 MeV/nucleon up to Kr, 15 MeV/nucleon up to Xe and 5 MeV/nucleon for U. High intensity beams with intensities up to 1 particle μA for ^{25,26}Mg, ^{30}Si, ^{37}Cl, ^{31}P, ^{48}Ca have been developed for the in-house heavy-element research effort. Energies above the Coulomb barrier for all ions became available when the superconducting ECR ion source VENUS was recently added to the injection system. The unique combination of high-intensity stable beams plus the high-efficiency Berkeley Gas-filled Separator is essential for the study of the production mechanisms, nuclear structure, and chemical properties of the heaviest elements. Other instrumentation housed at the 88-Inch includes the LIBERACE+STARS detector system, comprising six clover Ge detectors used in combination with a Si telescope array. This supports a broad physics program of nuclear structure, reactions, and astrophysics as well as applied work for Advanced Fuel Cycles and Stockpile Stewardship. A neutron beam line has been constructed to perform direct neutron reactions on radioactive targets of interest for these applications as well. The 88-Inch is also home to a laser trapping program for studies of fundamental symmetries.

Berkeley Lab scientists continue their development of powerful instrumentation and equipment for use by the nuclear physics community. Examples include the leading role they play in the development of the gamma-ray tracking arrays GRETINA and GRETA, and the development of the next generation ECR ion source, VENUS. VENUS is the centerpiece of an intensive R&D program to develop a high intensity heavy ion beam injector for FRIB. Recently VENUS successfully produced a uranium ion beam with intensity of up to 6 particle μA of U^{33+} and U^{34+}. In addition to its nuclear science program, the 88-Inch Cyclotron hosts the BASE (Berkeley Accelerator Space Effects) facility which provides beams for a wide range of radiation effects testing. For single event effects, those caused by an individual charged particle, cocktail beams (a mixture of heavy ions ranged from N to Bi, at energies of 4.5, 10 and 16 MeV/nucleon) with fast switching between ions of varying linear energy transfer were used. This is a unique feature of the combination of versatile ECR ion sources with a cyclotron. For cumulative radiation effects, protons or sometimes neutrons are employed, using the high intensity light ion capabilities of the cyclotron. The primary customer for the use of BASE is the National Space Security community; secondary users include NASA, various private electronics manufacturers both U.S. and international, small businesses, radiation biologists, high-energy physicists and accelerator designers.

Two major initiatives that scientists at the 88-Inch are pursuing, and that will need additional funding in the coming years, are CLAIRE (Center For Low energy Astrophysics and Interdisciplinary REsearch) and a next-generation, large-acceptance spectrometer. CLAIRE is envisioned to be the most advanced low-energy (< 3MV), high-intensity (> 100 mA) astrophysics accelerator dedicated to measuring key reaction cross-sections involved in hydrogen and helium burning phases of stars (including the "holy grail" of nuclear astrophysics, the $^{12}C(\alpha,\gamma)$ reaction). The large acceptance spectrometer is conceived as a multipurpose device, based on advanced superconducting magnet technology, that is capable of running in a dual mode – a) in vacuum mode at variable angles to allow Z and A identification of products from direct reactions (such as deep inelastic), opening the way to unique studies of nuclei far-from-stability, b) in gas-filled mode at zero degrees to give significantly improved performance for studies of the heaviest elements.

National Superconducting Cyclotron Laboratory

The operation of the upgraded Coupled Cyclotron Facility (CCF) at the National Superconducting Cyclotron Laboratory (NSCL) was included in the highest priority in the last long-range plan. The CCF started operation in 2001 and is currently the Nation's premier rare isotope facility. The beams from the CCF are primarily used to explore the properties of nuclei with unusual ratios of protons and neutrons, the nuclear processes that are responsible for the synthesis of the elements in the cosmos, and the isospin dependent properties of hot nuclear matter at sub- and supra-normal densities. The NSCL users and staff have been extremely productive with over 500 papers published in refereed journals, including 79 Physical Review Letters (since 2001). The university setting offers a unique synergy of education and research. About 10% of the Nation's Ph.D.s in nuclear science are based on experiments at the NSCL. The optimal utilization of the NSCL is critical to maintain U.S. leadership in rare-isotope science with fast beams and the education of the next generation nuclear scientists. Until a next generation facility for rare isotope beams (FRIB) becomes operational, the CCF will continue to be the Nation's premier rare isotope facility.

The in-flight production method allows the CCF to be very flexible. From 2001-2006 the facility delivered over 250 different rare isotope beams; on average 3.5 rare isotope beams per experiment. Typical beam energies range from 50 – 120 MeV/nucleon and experiments with beam energies as low as 5 MeV/nucleon have been performed. Experimental setups can utilize beams from very low ($10^{-5}s^{-1}$) to high intensities ($10^{8}s^{-1}$). The availability of the CCF of over 90% has been outstanding. The resulting reliable and predictable operating schedule is important for the large number of different experiments and users.

The laboratory continues to develop techniques and equipment that will be critical for the success of FRIB. It was the first facility to stop a fast rare isotope beam in a gas cell and used in new precision mass measurements of short-lived neutron- and proton-rich isotopes. Build on this success the NSCL is implementing full capabilities to perform experiments with reaccelerated beams produced with the gas-stopping technique. This development includes an advanced concept for a cyclotron gas stopper, an EBIT charge breeder and in the initial stage a reaccelerator up to 3 MeV/nucleon. A further upgrade to 12 MeV/nucleon is possible. When completed it will be the first facility in the world that will have the unique capability of reaccelerated beams produced from in-flight fragmentation. In order for the NSCL to remain a world-leading facility a major upgrade as outlined in the recent "Isotope Science Facility" white paper is needed in the longer term future.

The research at the CCF lays the groundwork on which a significant part of the scientific program at the FRIB will be built. The existing state of the art experimental equipment is already well suited for future use at FRIB. For example the high-resolution spectrometer S800, the low-energy beam and ion trap facility LEBIT, the segmented germanium array SeGA, the modular neutron array MoNA, the high-resolution charged particle array HiRA, and the beta-decay end station, are well matched for the currently proposed 200 MeV/nucleon energy of the FRIB. In addition, the NSCL continues to develop new equipment for rare-isotope research, for example a setup for laser spectroscopy of stopped rare isotopes and a highly efficient scintillator array are planned.

1.2. Low Energy University Based Facilities

The federally supported university-based accelerator facilities at Florida State, Notre Dame, Texas A&M, TUNL (Duke) and Yale constitute an extremely productive and cost effective component of the national program. Federal investment in these facilities is generally supplemented by significant state or university contributions. As a group the facilities serve a critical function as focal points for attracting and educating the next generation of nuclear scientists.

The John D. Fox Superconducting Accelerator Laboratory at Florida State University is based on a 9 MV FN tandem electrostatic accelerator with a superconducting LINAC booster. Unique capabilities include an optically-pumped polarized ^{6,7}Li source, and a sputter source dedicated to ^{14}C beam production. The facility provides in-flight production of radioactive beams with the RESOLUT beamline. RESOLUT is equipped with RF cooling and a high-acceptance magnetic spectrograph. Experimental tools include a Ge gamma-ray detector array and scattering chambers with a variety of highly-segmented charged particle detector arrays and a neutron wall. The recent installation of a university funded 210 W He refrigerator has led to more efficient operation of the LINAC and RESOLUT. Future upgrade plans include instrumentation for radioactive beam experiments and the addition of more LINAC resonators. The research with RESOLUT is focused on nuclear astrophysics, with an emphasis on stellar reactions and explosive nucleosynthesis. Another research topic is the identification of exotic isospin states with high-isospin beam and target combinations. Research with the ^{14}C beam and the Ge and Si detector arrays has explored the variation of shell gaps with neutron excess around the *s-d* shell.

The Notre Dame Nuclear Science Laboratory (NSL) has operated a successful program in nuclear astrophysics, nuclear structure physics, radioactive beam physics, and radiation chemistry for decades. The NSL operates three accelerators. The FN Tandem Pelletron is used for radioactive beam, nuclear structure and nuclear astrophysics experiments as well as for a program in radiation chemistry. Two low energy machines are used mainly for nuclear astrophysics. Applied programs have been developed in astrobiology in collaboration with radiation chemists and in archaeometry in collaboration with researchers from the Department of Anthropology. The radioactive beam program at NSL is centered on the TwinSol facility which utilizes two superconducting solenoids to separate radioactive beam products from primary beam. The TwinSol program is primarily directed toward the study of nuclear reaction mechanisms and the structure of unstable nuclei. The stable beam program in nuclear structure is focused on studies of masses far from stability, the structure of N=Z nuclei, the study of low-lying collective modes in deformed nuclei, as well as giant resonances. The nuclear astrophysics program uses two low energy high-intensity Van de Graaff accelerators to study reactions relevant to stellar hydrogen and helium burning, and reactions important in determination of flow patterns and break-out possibilities the cold and hot CNO cycles to at different stellar temperatures. A broad international program has been developed to investigate reactions of relevance for the p-process in type II supernovae. Complementary to these direct low energy reaction studies a variety of indirect methods have been developed to determine nuclear structure parameters for calculating reaction rates relevant to the hot CNO cycles and the rp-process. These efforts are accompanied by large scale reaction network simulations.

The centerpiece of the Texas A&M University Cyclotron Institute is a K500 superconducting cyclotron, from which first beams were extracted in 1988. Using two electron-cyclotron-resonance (ECR) ion sources, the accelerator can produce a wide variety of beams: those with intensities of at least 1 enA range in energy up to 70 MeV/nucleon for light-ions and to 12 MeV/nucleon for heavy-ions such as U. For the past decade the cyclotron has averaged more than 6500 hours of operation per year. Research at the Cyclotron Institute covers a broad range of topics in modern nuclear physics at low and intermediate energies. Recently, radioactive beams have become more of a focus for the laboratory. High-purity secondary beams are produced in the recoil spectrometer MARS via inverse-kinematics reactions. The BigSol spectrometer has been commissioned and now serves as a second location that provides radioactive beams. A complement of sophisticated, state-of-the-art detectors and spectrometers provides the instrumentation necessary for research in nuclear structure, weak interactions, exotic nuclei, nuclear astrophysics, intermediate-energy reaction dynamics, nuclear thermodynamics, the nuclear equation of state, atomic physics and applied nuclear science.

Over the past decade, use of the Texas A&M facility to test the response of electronic components to radiation has grown steadily; it now occupies about 20% of available beam time. The Radiation Effects Facility (REF) end station consists of dosimetry and energy degrader systems with computer-controlled device staging at test locations in both air and vacuum.

Cyclotron Institute staff members have developed a plan to upgrade the present facility to one that would yield high-quality radioactive beams directly from the K500 superconducting cyclotron. The first stage of the plan involves re-commissioning the 88" (K150) cyclotron. Intense light-ion and heavy-ion beams from that cyclotron will be used to produce radioactive ions, which will then be slowed down in a He-gas stopper and collected by ion guides as 1^+ ions. A 1^+-to-n^+ ECR ion source will then be used to produce the highly charged radioactive beams for reacceleration in the K500 cyclotron. The project, which has been underway for about two years will cost around $4 M to complete. It is envisioned that many aspects of the project will provide valuable input to FRIB development.

The Triangle Universities Nuclear Laboratory (TUNL) is a co-operative venture of the University of North Carolina, North Carolina State University and Duke University, and is located on the Duke campus. TUNL supports a broad fundamental nuclear science program in strong interaction physics at low energy, astrophysics, and electroweak interactions and fundamental symmetries, as well as an applied nuclear physics and interdisciplinary science program. TUNL operates three accelerator facilities, the tandem laboratory, the Laboratory for Nuclear Astrophysics (LENA), and the High Intensity γ-ray Source (HIγS). The tandem laboratory features an FN tandem accelerator equipped with the highest current DC source of polarized hydrogen ions in the world, along with the high-current, low energy beam facility (LEBAF). LENA delivers 0.1 to 5 mA beams of protons at energies between 0.2 and 1 MeV for study of astrophysically significant reactions. HIγS is operated as a collaborative effort of TUNL and the Duke Free Electron Laser Laboratory (DFELL), and is located at the DFEEL. This facility provides intense mono-energetic beams of polarized or unpolarized γ-rays, currently in the energy range of 2 to 50 MeV. A significant upgrade of HIγS, due for completion in 2008, will raise the upper energy limit to 250 MeV, and increase beam intensities. A broad spectrum of physics opportunities are foreseen at this unique facility.

The A. W. Wright Nuclear Structure Laboratory (WNSL) at Yale University houses a 20 MV ESTU tandem Van de Graaff accelerator capable of accelerating heavy beams to energies above the Coulomb barrier. The program of nuclear structure and nuclear reaction studies at WNSL focuses on symmetries, collective modes and structural evolution, phase transitions and critical behavior, p-n interactions, mixed-symmetry states, the production and structure of heavy nuclei, and nuclear astrophysics. The instrumentation suite at WNSL reflects the diversity of this program and consists of the YRAST Ball, a Ge clover γ-ray detector array, the ICEY Ball for conversion electron spectroscopy, SPEEDY+NYPD which couples Ge clovers with a plunger for recoil-distance lifetime measurements, a gas-filled spectrometer for spectroscopy of heavy nuclei, a moving tape collector for decay studies, a superconducting dipole magnet which can be combined with a moving tape collector and Ge detectors for magnetic moment measurements, and an Enge split pole spectrograph used principally by the astrophysics program.

1.3. Gammasphere

Gammasphere remains a central component in the highly successful U.S. nuclear structure program. Gammasphere's superb resolution, granularity, efficiency, and its ability to be used with auxiliary detectors continue to make it an unsurpassed device for studying rare and exotic nuclear properties. Between 2002 and 2006 over 230 refereed publications and nearly 40 Ph.D. dissertations have been written utilizing data from this detector system. The breadth of physics questions and nuclei investigated has been great, ranging from investigations of fundamental symmetries through measurements of positronium decay, to a study of ^{22}Mg impacting on astrophysical reaction rates, and to the beginning of a new chapter in gamma-ray spectroscopy - the study of shell-stabilized super-heavy nuclei. Between these extremes Gammasphere was of central importance to the study of shell structure, investigation of states with the highest possible spins in nuclei, and the exploration of the coexistence and competition of nuclear shapes.

The tremendous significance of these scientific discoveries (and many others not mentioned) illustrates the continued vitality of the Gammasphere program and the key role of gamma-ray spectroscopy in our quest to understand nuclear structure. Gammasphere remains in constant high demand from its large user community. There is every reason for it to remain wonderfully productive in the future provided adequate support for maintenance and essential upgrades is continued.

2. Future Facilities and Instrumentation

There is a broad consensus among researchers in low-energy nuclear science that a major investment by the U. S. in an advanced facility dedicated to the study of nuclear science with radioactive ion beams is critically needed to maintain the health of our field. Science with rare isotope beams is being vigorously pursued around the world. This broad international effort will influence, enhance and benefit the U. S. program. However, it would be a mistake to imagine that U.S. investment in any of the foreign-based facilities now under construction or consideration would provide an adequate substitute for the far-reaching impact which FRIB will provide. FRIB is the future of the study of nuclei, and nuclear astrophysics in the United States.

Leadership-class experimental instruments are also critical to the future of our field and to the effective and efficient utilization of FRIB. The delay and de-scoping of the original RIA concept makes the development of powerful and innovative instrumentation more important, and at the same time may make it more difficult, since large-scale dedicated funding for instrumentation at FRIB is not anticipated. These considerations require that development of instruments (and beam delivery capabilities) at existing facilities be supported vigorously; the suite of instruments developed or improved over the next decade will form the basis of the FRIB program at startup.

2.1. Facility for Rare Isotope Beams

The highest priority for new construction of the Nuclear Structure and Astrophysics community is an advanced FRIB. The current vision of this facility is a reduced-scale version of the RIA concept that was discussed and recommended in the 2002 Long Range Plan; this facility would have a cost of less than half of that estimated for the full RIA facility. The technical goal is to provide the community with greatly enhanced experimental access to isotopes away from the valley of stability which hold the keys to unlocking many of the mysteries of nuclear structure and the cosmos, as well as providing unique tests of the standard model of particles and interactions and a bounty of isotopes for applications to science, technology and medicine. The National Research Council Rare Isotope Science Advisory Committee (RISAC) concluded in 2006 that this science should be a high priority for the United States. The Department of Energy has declared its intention to start project engineering of a U.S. exotic beam facility for about half the cost of RIA with unique capabilities in 2011. RISAC concluded that such a facility would provide capabilities unmatched elsewhere. FRIB will include the capabilities for stopped, re-accelerated and in-flight beams to realize the scientific potential defined by the community and endorsed by the RISAC report.

FRIB is based on a superconducting heavy ion driver linac capable of producing 400 kW beams (the same beam power as RIA) of all elements from uranium at 200 MeV/nucleon to protons at 580 MeV. Heavy ion beams are delivered to a high power target, with the resulting rare isotopes being collected in a two-stage fragment separator and delivered to a gas-catcher. The extracted ions are purified by an isobar separator and then either used directly in stopped ion experiments or injected into a charge breeder to be accelerated to energies required for nuclear astrophysics and nuclear structure research. After the separator the rare isotopes can also be delivered directly to experimental instruments for research at ~150-200 MeV/nucleon. The production of rare isotopes via spallation or fission of heavy targets with high power light ion beams in an ISOL facility for extraction and delivery to the stopped and reaccelerated beam research areas can also be implemented.

In the global context this FRIB concept is very competitive. First of all, the reaccelerated beams based on the heavy ion driver and gas catcher concepts are not included in any current or planned facility worldwide. And 400-kW heavy and light ion beams from the driver support production of the highest intensity rare isotope beams for both in-flight and ISOL-based research.

For stopped and reaccelerated beams, the capabilities of FRIB are quite similar to those projected for RIA for over 80% of the isotopes produced. The rates for fast beams are still at least an order of magnitude higher than RIKEN's RIBF and GSI's FAIR facilities. The retention of technical capabilities in the reduced-cost facility that comparable to those of RIA is largely due to the significant progress made in the past few years through the RIA R&D program. Specifically, maintaining the full 400-kW beam power in the driver required both the increased ECR ion source performance that has been demonstrated recently with the VENUS project at LBNL and the two-charge state injector and multi-charge-state acceleration developments.

On the other hand, significant capabilities had to be sacrificed to reduce the cost to less than half that of RIA. These include: 1) an approximately order of magnitude decrease in performance for those isotopes that are most efficiently produced by in-flight fission of uranium beams, 2) no multi-user capability in the baseline, 3) reduced intensities of rare isotope beams for masses less than 70 at astrophysics energies due to the elimination of the 1+ injector, 4) smaller experimental areas, 5) no new experimental equipment in the baseline facility cost, and 6) reduced purity of heavier in-flight beams due to the broader charge state distributions at the reduced energy. The fact that no new research instruments are included in the baseline cost estimates of FRIB is compensated for by the facts that the secondary beam energies are well matched to the capabilities of existing instruments in the US and there will continue to be developments of new instruments, such as Greta, in the US that are also well matched to the needs of FRIB. These instrumentation developments are discussed in the next section.

2.2. Equipment Development for FRIB

The new proposals for a reduced cost-option for FRIB eliminated funds for new experimental equipment. Although any new facility should be equipped with state of the art new equipment the situation for FRIB differs significantly from other major nuclear physics facilities that were brought online over the last years. Both RHIC and CEBAF both ventured into completely new domains in terms of beam energy. The experiments proposed at these facilities required the design of large, dedicated, experimental setups that were optimized for the significantly higher energies. None of the existing detectors were adequate to be used at these new facilities. The design and construction of these new detectors had to move forward simultaneously with the construction of the accelerator in order to be operational when the first beam became available.

The proposed primary beam energy of 200 MeV/nucleon for FRIB does not produce rare isotope beams with completely different properties than at current facilities. For example, the most of the existing experimental equipment at the CCF is designed for rare isotopes produced by 200 MeV/nucleon primary beams. The new domain of FRIB is the large beam power, which will produce more exotic neutron- and proton-rich isotopes at higher intensities. Overall the requirements for the detectors at FRIB are essentially the same as for the currently existing detectors at ANL, HRIBF and NSCL. The techniques and the intensities for the rare isotopes are the same. The main and most important difference is that the isotopes studied are not the same. Isotopes much further from the line of stability will become accessible.

Thus the equipment currently in use at operating facilities is well suited to be used at FRIB. For example, SeGA, MoNA, HiRA, LEBIT, and the S800 at NSCL and the CPT, APT, laser atom traps, split-pole spectrographs, and the FMA at ANL are used routinely for rare isotopes experiments. In addition, new devices are continuously being developed to optimize the use of the rare isotope beams. Examples include ORRUBA (HRIBF), HELIOS (ANL), a high-efficiency scintillator array (NSCL) and collinear laser spectroscopy setups. For gamma-ray spectroscopy GRETINA/GRETA developed at LBL will significantly increase the resolving power at any facility. In addition to the activities at these national laboratories, users at university laboratories are also very active in equipment and technique development. The rf separator RESOLUT at FSU and the initiative at Texas A&M to design a large acceptance spectrometer are examples. All these developments are absolutely essential in order to ensure that state-of-the-art equipment will be available when FRIB begins operation.

Although no dedicated funds for specific equipment at FRIB are necessary, it is absolutely essentially to adequately fund the continued development of state-of-the-art detectors at existing facilities that can be utilized at FRIB when it becomes operational.

2.3. GRETINA and GRETA

The development of radioactive beam capabilities around the world is opening a new landscape for discovery, and the connections between nuclear structure studies and astrophysics, neutrino physics, and physics beyond the standard model are stronger than ever. New detector technologies are evolving which can meet the challenges of the new generation of experiments. Leading these is the technology of "gamma-ray tracking" which will revolutionize gamma-ray spectroscopy in a way similar to that in which large arrays of gamma detectors did a decade ago. During the last few years this technology has been shown to be feasible and GRETINA, a 1π detector, is under construction. However, a 4π GRETA system is urgently needed to fully exploit the science opportunities at radioactive beam facilities and to increase the reach of stable beam facilities. In addition, gamma-ray tracking technology has important applications for science, medicine, and homeland security.

GRETA will improve the power of GRETINA by a factor of 10 to 100 for most experiments. In addition, next generation auxiliary detectors will further enhance the performance of GRETA which is crucial for achieving the ultimate sensitivity. This will greatly extend the reach of the physics allowing advances in the study of nuclear structure, nuclear astrophysics, and fundamental interactions. For example, the alteration of shell structure and new collective phenomena at the two extremes of isotopic number can be studied from ^{48}Ni to ^{80}Ni. The structure of heavy elements with Z larger than 106 can be studied with enough detail to help constrain predictions of the stability of super heavy elements. Hyperdeformed nuclei with 3:1 axis ratio at the very limits of angular momentum will be within reach. In nuclear astrophysics, measurements of crucial capture reactions require detectors with the highest possible efficiency. In the area of fundamental interactions, GRETA's high spatial resolution and efficiency will bring a large increase in sensitivity to a wide range of measurements.

GRETA was first mentioned in the 1996 Long Range Plan and became a recommendation in the 2002 LRP. In the 2003 NSAC report entitled "The Nuclear Physics Science Horizon: Projects for the Next Twenty Years" GRETA obtained the highest rank in both science and readiness categories. Since that time, the GRETINA project has developed all of the advanced technology required for GRETA. The first detector module with four highly segmented irregularly shaped crystals in a single cryostat has been produced. Signal digitizers with the required resolution and sampling rate have been fabricated and are in use. Signal decomposition and tracking software have already demonstrated the required position resolution and speed.

Detailed GRETA cost and schedule estimates have been developed based on the current GRETINA project. The project could be completed in 2016. Detector production defines the critical path and a smooth transition from GRETINA to GRETA with no gap in detector production is assumed. The physics program will start in 2008, and grow in discovery potential as detectors are added, with the full system ready prior to the planned operation of FRIB in 2017. A competing European gamma-ray tracking project AGATA is planned to be completed in 2016.

As stated in the 2002 NSAC Long Range Plan, "The detection of gamma-ray emissions from excited nuclei plays a vital and ubiquitous role in nuclear science. The physics justification for a 4π tracking array is extremely compelling, spanning a wide range of fundamental questions in nuclear structure, nuclear astrophysics, and weak interactions. This new array would be a national resource that could be used at several existing stable and radioactive beam facilities, as well as at RIA." We strongly urge the timely completion of the full 4π system GRETA, with construction beginning immediately upon the successful completion of GRETINA.

Useful Links:

ANL
    http://www.phy.anl.gov
HRIBF
    http://www.phys.ornl.gov
LBL
    http://cyclotron.lbl.gov
NSCL
    http://www.nscl.msu.edu
FSU
    http://www.physics.fsu.edu/Nuclear/Brochures/SuperconductingLinearAcceleratorLaboratory
Notre Dame
    http://www.nd.edu/~nsl
TAMU
    http://cyclotron.tamu.edu/
TUNL
    http://www.tunl.duke.edu/
YALE
    http://wnsl.physics.yale.edu/
Gammasphere
    http://www-gam.lbl.gov/
GRETINA
    http://grfs1.lbl.gov
ANL/CARIBU
    http://www.phy.anl.gov/atlas/caribu.html
NSCL/ISF
    http://www.nscl.msu.edu/future/isf/
HRIBF Upgrade plans
    http://www.phy.ornl.gov/hribf/initiatives/