Nuclear Structure and Astrophysics Town Meeting

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Executive Summary

The town meeting on Nuclear Structure and Nuclear Astrophysics took place November 14-17 at the Oakland Convention Center in Oakland, California. The meeting was organized parallel to the town meeting on Astrophysics, Neutrinos, and Symmetries. Despite the short notice and severe budgetary constraints, approximately 200 participants attended the town meeting from all of the national laboratories and a wide range of universities in the United States and Canada. The meeting centered around discussion sessions consisting of ten working groups where the average individual attendance ranged between thirty and fifty participants. Scientific opportunities for low energy nuclear physics and astrophysics, the need for new instrumentation at existing facilities, and the future of both undergraduate and graduate education with respect to satisfying future national demands for nuclear scientists were discussed.

The emerging topic of greatest interest was the construction of the next generation radioactive ion beam facility RIA (Rare Isotope Accelerator) and its implications for the future of the field. The community unanimously endorsed that the construction of RIA will provide unprecedented new opportunities by opening entire new vistas in nuclear structure, nuclear dynamics, and astrophysics. The construction of RIA would also offer a wide range of new possibilities for nuclear science applications in medical diagnostics and therapeutics. Some other developing areas of nuclear science applications for RIA include biology with the new genomics explosion, materials science, stockpile stewardship, and reactor research.

Considerable progress has been made in the last decade at national and university based laboratories in the development of radioactive ion beam techniques and their use in studying a wide range of scientific problems. In particular the recent upgrade of the NSCL coupled cyclotron offers a multitude of experimental opportunities. This broad range of technical opportunities and intellectual input remains vital for the field and needs to be strengthened to explore all of the opportunities low energy nuclear science offers for society. The demands in development and manpower, but also the enormous scope of scientific and technical opportunities RIA will offer, requires a broad range of complementary facilities and efforts which can only be achieved by maintaining and strengthening the present laboratories. Concern was expressed about the need to strengthen nuclear theory as well. New efforts and initiatives in nuclear theory will not only be vital for the successful development of the scientific program at RIA but also for maintaining the primary position of nuclear knowledge and know-how for the US nuclear science community.

New opportunities for nuclear astrophysics arise with the possibility of the construction of a US underground laboratory facility for the next generation of neutrino detectors. Such a facility could provide the site for a low energy underground accelerator laboratory to address the nuclear astrophysics needs in low energy cross section data with stable beams. Such an accelerator laboratory should complement and surpass the present European efforts at the Gran Sasso laboratory in Italy.

The installation of a next generation neutrino detector, such as ORLaND at the Oak Ridge spallation neutron source, SNS (which also produces copious neutrinos by pion-decay at rest) offers new possibilities in measuring the reaction rates for neutrino induced processes of importance for supernovae nucleosynthesis. This would open new opportunities for the nuclear astrophysics community. The nuclear structure and nuclear astrophysics communities therefore endorse the activities to design and construct a new facility.

The town meeting culminated in the formulation of a set of four recommendations for the long range planning committee.

Recommendation #1
The highest priority for the nuclear structure and nuclear astrophysics communities is the construction of RIA as the world's premier facility for the study of exotic nuclei and the pursuit of the associated exciting physics opportunities. These encompass the understanding of nucleonic matter – from the nucleus to neutron stars, – the origin of elements, the quest for the nature of stellar explosions, and tests of fundamental interactions and conservation laws in nature.

Recommendation #2
The scientific program of our communities is driven by the vigorous and continuous support of forefront research opportunities at existing national and university laboratories. Based on the scientific potential, the NSCL upgrade was prioritized in the previous Long Range Plan. In order to realize the exciting scientific opportunities now available, the operation and use of the facility should be strongly supported.

University based research groups and laboratories are the lifeblood of our field. Federal investment should be strengthened in order to maintain competitiveness in research and to provide the best possible training for future generations of scientists for our fields and to serve the national needs of our society.

The development of new instrumentation and technologies such as a gamma-ray tracking device represents the key for new discoveries at present and future facilities and should therefore be strongly supported.

Recommendation #3
To take full advantage of the exciting science opportunities provided by RIA and the next generation neutrino experiments, a theory initiative is needed. This initiative will invigorate the field of nuclear structure, nuclear reactions, and nuclear astrophysics by creating new bridged faculty positions, and postdoctoral and student positions. It will also provide additional resources to universities and national laboratories for innovative approaches to the nuclear many-body problem, its astrophysical applications, and the development of a multidimensional supernova model.

Recommendation #4
The resolution of crucial questions in stellar evolution relies on the use of intense low-energy stable beam accelerators. We strongly endorse the effort to explore the advantages and feasibility of a US National underground facility as a site for a low background accelerator laboratory.

Statement of Endorsement
Closely associated to our interpretation of stellar processes from Sun to supernova is the understanding of weak interaction and neutrino induced processes. Our community therefore endorses the efforts in pursuit of a new neutrino laboratory.

To evaluate these recommendations within the context of all of the nuclear science efforts NSAC has provided a list of questions that need to be addressed. A detailed discussion of the various points is presented in the following sections; here we only present a short summary in response to the NSAC questionnaire.

Answers to NSAC Questionnaire

- *What scientific question(s) is this sub-field trying to answer?*

Nuclear structure physics seeks to understand the nature of nucleonic matter (its phases and modes at various distance scales) and tries to develop a unified microscopic description of the nucleus. There are many questions about the nature of nucleonic matter that fall under this overall goal. What combinations of protons and neutrons can form an atomic nucleus? What are the appropriate degrees of freedom to describe nuclei? How does nuclear behavior change at extremes in spin, proton-to-neutron ratio, and excitation energy?

Nuclear astrophysics is concerned with the impact and influence of nuclear structure and nuclear reactions on the evolution, energy generation, and time scales in stars and stellar explosions. What is the origin of the elements that make up the present day Universe?

- *What is the significance of this sub-field for nuclear physics and for science in general?*

The nucleus is the *Core of Matter, the Fuel of Stars.* Nuclear structure and nuclear astrophysics deal with a plethora of phenomena, which define and determine the evolution of our Universe. One of the prime goals of nuclear physics is to understand the

nature of the nucleus and its impact on the Universe. Nuclear structure and nuclear astrophysics attempt to address this problem.

The nucleus is a quantum object with a finite number of components. The fact that Weak, Strong, and Coulomb forces all contribute to the nature of the quantum system further enhances its interest. The study of the nuclear quantum system is closely related to the problem of understanding small-scale systems where quantum mechanics plays a dominant role. There is a strong intellectual connection between nuclear science and the science of mesoscopic systems. As science and technology move to smaller and smaller scales the quantum science of nuclei will be more relevant to progress in many areas of physics and biology.

Nuclear astrophysics investigates the role of the nuclear microscopic system on a macroscopic (stellar) scale. It interfaces between observational astronomy and theoretical astrophysics and the hydrodynamics of slowly evolving stars and rapid stellar explosion. Its observational signatures are the galactic abundance distribution, the specific abundance distributions in stellar atmospheres and stellar explosions, the magnitude and time dependence of stellar luminosities, the appearance and distribution of galactic radioactivity, and the characteristics of neutrino flux from the sun, from cataclysmic binaries, and from supernovae. Through these signatures the field is closely linked to the latest observational results of satellite based telescopes.

With the launch of a new generation of satellite based telescopes from the Compton Gamma-Ray observatory to HUBBLE and CHANDRA, a wealth of new data has been accumulated. This provided new insight in the number and nature of r-process sites, in nova and supernova nucleosynthesis, and in the nature of X-ray bursts. New ground based observatories are presently being constructed, the next generation Gamma-Ray observatory INTEGRAl will be launched in the near future; this will. All these future projects identify the observation and understanding of nucleosynthesis processes as one of the highest priorities for their scientific mission. Cosmo-chemistry has developed a powerful approach to complement the observational results. Improved analysis of meteoritic inclusions has provided extreme detailed data about the abundance distributions in condensates from the winds of late stars to the ejecta of novae and supernovae. Nuclear science data is critical to reap the full scientific benefit of all these investments.

The nucleus can also serve as a laboratory to study fundamental interactions and hence this sub-field has a strong connection to the goals of particle science. Because the nature of nuclei is governed by three of the four forces in nature there are manifestations of the fundamental interactions that can be used to search for physics beyond the standard model.

- *What are the achievements of this sub-field since the last long-range plan?*

The last several years have witnessed enormous advances in nuclear structure physics that are propelling the field into new areas that will ultimately be fully realized with the construction and exploitation of the unique capabilities of RIA. With continuously strong activities on the evolution of structure in stable nuclei with mass, energy, and angular momentum, the main focus has shifted to include also the evolution of structure with isospin, towards the limits of particle stability.

The landmark experimental research achievements on nuclei at or near stability include:

- New modes of nuclear collectivity as manifest in the phenomena of magnetic rotation (shears bands), chiral bands, and wobbling modes in triaxial nuclei.
- Search for and characterization of low and high-energy multi-phonon states in both spherical and deformed nuclei.
- Discovery of superdeformation and collective bands in light nuclei and the detailed spectroscopy of superdeformed nuclei, which demonstrates the validity of the extreme single-particle picture at very high spins.
- Study of shape/phase-transitional behavior in nuclei and the development of new analytic descriptions of critical point nuclei.
- Systematic measurements of the giant isoscalar monopole resonance, which set the new limit on nuclear incompressibility.
- Studies of the GT strength in charge-exchange reactions that shed new light on the importance of delta excitations in nuclei.
- Extensive new measurements of nuclear masses, with implications both for structure and astrophysics.
- New studies of the response of the nucleus to small and large density oscillations and an improved characterization of the nuclear equation of state.
- Evidence for the existence of nuclear supersymmetry in the level structure of quartets of even, odd, and odd-odd heavy nuclei.

An unprecedented number of advances have been made in understanding the nature of exotic nuclei; the heaviest nuclei, proton rich nuclei, and neutron rich nuclei.

- Advances in the production and identification of heavier and heavier new nuclei, pushing now to $Z=118$.
- Discovery of new double-magic nuclei ^{48}Ni, ^{78}Ni, and ^{100}Sn.
- Probing the proton drip line cumulating in the discovery and spectroscopy of spherical and deformed proton emitters and first evidence for two-proton radioactivity.
- Discovery and investigations of exotic nuclear topologies, such as halo nuclei that focus attention on nuclear structure that was unforeseen.
- Spectroscopy of heavy $N=Z$ nuclei was pushed to $N=Z=44$.

The theoretical nuclear structure research achievements include:

- Ab initio Monte Carlo calculations for light nuclei, including detailed description of the structure and reactions of nuclei with $A<11$.

- Ab initio no-core shell-model calculations based on bare NN interactions. New insights on effective interactions from the effective field theory.
- Revolution in the shell model technology, including large-scale shell-model calculations for the collective structures and the stellar weak interaction rates in the medium mass nuclei, and the description of neutron-rich nuclei at the interface between shells
- Coupling of reaction theory with nuclear structure. Coupled-channel description of light halo nuclei and proton emitters, and continuum-shell-model calculations for light nuclei.
- Theoretical studies of the mean field description of near drip line nuclei, of alterations to the underlying shell structure or even of the validity of the notion of single particle motion itself, study of the evolution of effective interactions in weakly bound systems, the incorporation of the continuum in microscopic descriptions of such nuclei, and the study of the origins of the spin-orbit force and its behavior in dilute density regions.
- Discovery of the origin of pseudospin symmetry from the Dirac equation.
- Advances in theory of high spins, including explanation of magnetic rotation and of the shears mechanism in terms of three-dimensional rotation, systematic explorations of time-odd fields in rotating nuclei, and realization that high-spin bands are superb examples of pure single-nucleonic motion in a rotating deformed potential
- Development of new theoretical paradigms for critical point nuclei and the nature of shape transitions.
- Explorations of interdisciplinary aspects of the nuclear many-body problem, including investigations of robust observables given random interactions; studies of clusters, nanostructures, and superconducting grains.

The recent achievements in nuclear astrophysics are manifold; they range from new observational data, to computational break-through in stellar and nucleosynthesis modeling, to new experimental data.

- A broad range of new experimental initiatives has carried the field through the last decade. These include the first successful measurement of a nuclear reaction at solar energies, major break-through in the determination of the $^{12}C(\alpha,\gamma)$ reaction rate, the identification of s-process branching points as a stellar thermometer. A series of successful experiments were performed with the first generations of radioactive beam facilities aiming at the understanding of the hot CNO cycles and the break-out from the cycles to the rp-process. Detailed measurements of rp- and r-process waiting point nuclei were performed and set stringent limits on the nucleosynthesis models. Studies of and on ^{44}Ti, ^{26}Al isotopes have provided important information on galactic radioactivity sources.
- With the launch of a new generation of satellite based telescopes from the Compton Gamma-Ray observatory to HUBBLE and CHANDRA, a wealth of new data has been accumulated. This provided new insight in the number and nature of r-process sites, in nova and supernova nucleosynthesis, and in the nature of X-ray bursts. Improved analysis of meteoritic inclusions has provided extreme

detailed data about the abundance distributions in condensates from the winds of late stars to the ejecta of novae and supernovae.

- A broad range of theory initiatives and collaborations have formed to improve the computational techniques and develop self-consistent two- and three-dimensional models for stellar evolution and stellar explosion. Independent of modeling the hydrodynamical aspects, large-scale nucleosynthesis models have been developed and have been applied for a broad range of scenarios including X-ray bursts and merging neutron stars.

- *What are the theoretical and experimental challenges being addressed by this sub-field (a) in the immediate future (<3 years) and (b) over the duration of the next long-range plan (10 years)? Identify the plans and the new opportunities, which will contribute to this scientific endeavor.*

Nuclear structure experiments will continue to explore the nuclear structure near and at the proton drip line, and will attempt to push the experiments into the realms of neutron rich regions of the nuclear landscape. Focus will be the interplay and evolution of single particle structure and collective behavior such as

- shell structure and shell quenching
- rotational structures and novel nuclear deformations
- vibrational modes

with increasing angular momentum and/or isospin. These experiments will rely on the use of Gamma-detector arrays and other advanced instrumentation at Argonne, Berkeley, and Oak Ridge National Laboratories, at the NSCL and other university based laboratories. Furthermore the study of particle decay modes towards the drip-lines and with evolving cluster structure will make use of increasingly complex particle strip detector arrays. Complementary experiments will utilize the radioactive beam capabilities of the HRIBF facility at Oak Ridge National Laboratory and of the NSCL at Michigan State University. Other important goals will be to expand the exploration of halo structure towards heavier mass neutron rich nuclei and to further probe the nuclear equation of state through continuo investigation of giant resonant behavior. A large amount of scientific effort in the next few years will concentrate in the R&D for the design and development of techniques and equipment for RIA and associated detector facilities.

The long-term future in the study of exotic nuclei is linked to the availability of RIA. RIA will allow us to follow the evolution of structure beyond the limits of stability:

- RIA will establish the limits of nuclear existence towards the neutron drip line for intermediate mass nuclei up to $Z \approx 40$ and allow the full exploration of nuclei along the r- and rp-process path.
- RIA will help to study the evolution of structure up to 20 neutrons beyond the line of beta-stability.
- RIA will also be a major tool in the goal to answer the quest for superheavy elements beyond the presently known limits of heavy elements.

- RIA will fully map the proton drip line in odd-Z nuclei and study exotic decay modes on this side of beta-stability.

Theoretical efforts in the immediate future will continue the refining development of the no-core shell model expanding to nuclei in the sd-shell. A universal shell-model interaction will be developed for a detailed description of medium mass shell nuclei. Continuum shell-model calculations with more than one particle in the continuum are another goal for the near future. This will be accompanied by the development of energy density functionals to describe global properties of nuclei, masses, rotational structure, and giant resonances. The long-range future may bring a shell-model description of medium-mass and heavy nuclei. Large efforts may also concentrate on the microscopic description of fusion, fission, cluster phenomena, and α-decay processes.

Nuclear astrophysics in the near future will branch their efforts to study reactions of relevance for explosive hydrogen and helium burning using the radioactive beam capabilities at HRIBF in Oak Ridge National Laboratory or at the just commissioned ISAC facility at TRIUMF, Canada. Astrophysics related experiments near the proton drip line will utilize the unique capabilities of the coupled cyclotron facility at the NSCL. With the successful production of neutron-rich isotopes, the NSCL coupled cyclotron facility and the HRIBF will provide also the first opportunity for r-process experiments. The higher energy rare isotope beams at the NSCL will allow charge-exchange studies that will address many of the needs for the determination of weak interaction rates in high density, electron degenerate environments such as pre-supernova core evolution. The measurements of Gamow-Teller distributions can be used to calibrate and refine large-scale shell model calculations. In addition, spin-dipole and M1 excitations can be used to probe nuclear structure relevant to neutrino interaction in stellar material.

Low energy stable beam efforts in the next few years will concentrate on experiments with very low energy intense ion beams (LENA), on the improvement and development of more efficient inverse kinematics techniques (JINA) and on the further exploitation of indirect methods through transfer and scattering experiments (Yale, Texas A&M). Neutron beam activities will depend on the future development at ORELA. TUNL will also foster the development of inverse reaction techniques using a Free Electron Laser photon source. Parallel to these efforts the community will explore the possibility, the advantages and disadvantages of an underground accelerator laboratory for the long-range future of the field.

In the long term the nuclear astrophysics community will exploit the opportunities offered by RIA to measure the detailed reaction mechanisms along the rp-process path and to explore the r-process up to the presumed fission endpoint. Complementary to these efforts will be the development of an underground accelerator facility.

- *What resources, including manpower, will be needed throughout the duration of the next long-range plan (with some attempt at priorities)?*

The nuclear structure and astrophysics community is currently using a fairly broad range of university and national laboratory based low and medium energy accelerators with light ion and heavy ion beams to maintain its ongoing research program. It relies on the continuing existence of these facilities as a base and on the parallel development of separator and detector devices to improve the experimental sensitivity. However, there are considerable needs in detector development and for the construction of future facilities to keep the field active and successful in the long term.

- This in particular requires extensive research for the development of a future gamma-ray tracking device, which will address a broad range of scientific and application needs.
- The anticipated research program will center on the use of radioactive beams at the existing facilities for the near future. A long-range worldwide competitive program, however, requires the design and construction of the next generation radioactive beam facilities, the rare isotope accelerator RIA.
- The nuclear astrophysics community in particular feels the increasing lack of suitable low energy accelerator facilities. While in the past the research program of this field was spread over a wide range of primarily university-based accelerators it is now centered at only a few laboratories. This process will continue in the near future. The construction of an underground accelerator laboratory may foster this process even further. The advantages and disadvantages of such concentration need to be carefully considered for a field of such scientific and experimental diversity.
- The successful implementation and application of nuclear physics data in astrophysics models requires a strengthening of the nuclear astrophysics data program. This program must be developed in close collaboration between experimentalists and modelers to optimize its structure, efficiency, and impact on the field.

Progress in the field was carried by a large number of small and medium sized university and national laboratory groups with an average of two/three graduate students. A recent analysis showed that in the past there were always ample job opportunities in academia, industry, and research to maintain and justify such a pool of students. While the demand on PhD's is growing, in particular for industry and medical related applications, the number of students is in decline, mainly due to the reduction in faculty positions in this field. This trend needs to be remedied to maintain an active and young program. Such a program will be necessary for the successful operation of RIA after it has been built. A series of advertisements and recent appointments, in nuclear astrophysics, in particular seems to signalize a turn to the better.

The existing theory programs in the areas of nuclear structure, nuclear astrophysics, and neutrino physics are small. In order to obtain the maximum benefit from planned experimental initiatives, it is therefore essential to revitalize the supporting theory. In

particular, because nuclear structure theory and nuclear astrophysics theory are well represented in only a few universities, it is essential to establish a national program that would encourage universities to invest in these areas.

- *How does the U.S. effort in this sub-field compare to the rest of the world and how do U.S. studies fit into the global picture?*

The progress in nuclear structure and nuclear astrophysics is based on international collaboration and exchange of ideas. Therefore many parallel and common goals can be identified in the present activities and in the design of future initiatives. The main activities outside the US are centered at facilities in Europe and Japan. Their infrastructure shows similarities with the US, several medium sized centers on the national laboratory level with a slightly higher number of university laboratory facilities. Also, strong similarities exist in the short and long-range goals for the future directions of the field.

- A very active program in physics with exotic beams has developed both in Europe and Japan, but smaller scale initiatives do also exist in India and China. While the Japanese efforts center on one facility at RIKEN, multitudes of European initiatives have been developed or have been proposed on a national and European level. These plans are conducted through NuPECC as the main European advisory body to the European funding agencies. The present US activities in exotic beam physics are centered at the NSCL at Michigan State University and at the HRIBF at Oak Ridge with several smaller facilities at other institutions. With these facilities being operational the US presently maintains a very competitive program worldwide. With ISAC coming on-line in Canada, SPIRAL in France, and REX/ISOLDE at CERN the US efforts will face very strong competition soon. For the long-range future major upgrades at RIKEN (Japan) and GSI (Germany) have been proposed which will take the leading role in the research with exotic beams outside the US. With RIA the US community proposes a superior facility, which will leap frog over all others and will dominate the field worldwide due to the superior combination of ISOL and in-flight techniques.
- Nuclear astrophysics research in stellar evolution is clearly dominated by the European efforts. New developments in inverse kinematics techniques are dominated by ERNA which is presently being constructed at the Ruhr-University of Bochum (Germany), comparable US efforts are presently being pursued at Notre Dame. LUNA as European pilot project for an underground accelerator laboratory has just received a major upgrade through Italian funding sources. There is no US underground laboratory; similar activities are presently centered on the low energy laboratory LENA at TUNL. The possibility and advantages of a US underground accelerator facility need to be explored. The center for astrophysics research with neutron beams has shifted to Europe. With the installation of n-TOF at CERN as a large European collaborative effort a new center for s-process and p-process measurements has emerged complementing the

activities at the Forschungszentrum Karlsruhe. In the long-range future the proposed European spallation source at Jülich may provide a new or additional site for the next generation neutron source. The US community operates ORELA at Oak Ridge and MLNSC at Los Alamos, both are potentially competitive and complementary facilities; the spallation neutron source SNS at Oak Ridge does offer great future opportunities, however at the present limited funding level it will be extremely difficult to recreate a competitive program.

- Parallel to the US, strong initiatives for designing new generations of scientific instrumentation like Gamma-tracking detector arrays exist in Europe. Several designs have been developed and have received significant R&D funding through a net of national and European sources.

- *What will the impact of the proposed program be on other fields and on society?*

There is always interaction and overlap between the different branches of science. Nuclear astrophysics itself emerged from intellectual interplay between nuclear physics and astrophysics. The nuclear many-body problem has numerous connections with other fields of science, including various sub-disciplines of physics, chemistry, numerical methods, large-scale computing. But there is an incredible range of other applications, directly linked to success and breakthrough from science and engineering to the arts and history.

- Low energy nuclear science techniques and developments play an important role in material science, ranging from the use of neutron scattering, tracer ion implantation, and PIXE/PIGE in solid state analysis and structural diagnostics to μSR/β-NMR in chemistry and biology.
- Nuclear science techniques for testing radiation detectors or for simulating the radiation flux in outer space are widely used in the US space program
- Nuclear science techniques provide an important analytical tool in the geo-sciences, from vulcanology to oceanography. An important asset is its use as an exploratory tool for new natural resources.
- Nuclear science based techniques are used in art analysis and in history and archaeology. Dating of ancient samples, like the Tyrol iceman, reveals the origin of mankind, dating the Turin Shroud complements our religious beliefs.

All of these applied and interdisciplinary research activities provide an array of important benefits to mankind, society, and the nation. A broad program has already been developed at existing accelerator and radioactive beam facilities worldwide and will be strengthened further with the construction of RIA. Nuclear science methods and techniques however also have a broad application, that directly affect our daily life. This includes foremost the vast range of medical applications which have grown rapidly over the last decades and which are accelerating into the future. Developments that demand more and more nuclear science personnel to make the next generation development in applied research techniques, as well as progress in computational techniques and software, include:

- the design and use of low energy accelerators for cancer therapy methods with light and heavy ions,
- the design and development of detector and multi-detector arrays possibly including tracking methods for gamma-camera and PET diagnostics and other imaging techniques,
- radioisotope production for medical treatment and diagnostics, and biomedical research.

While medical applications clearly have a dominant impact on daily life, other issues, like energy resources and safety and security, belong to the classical realm of nuclear science applications, which also will be addressed and extended through RIA. This includes the continuing development of ultra-sensitive and high-resolution detection techniques with accelerator mass spectroscopy, gamma detectors, X-ray, γ-, n-, p-scanners:

- for environment, nuclear energy and nuclear waste storage, as well as a broad range of national security concerns
- for dosimetry, safety and security checks, nuclear forensics, and a broad range of industrial applications.

In addition, nuclear science techniques, developments and manpower are needed to handle our nuclear heritage and, eventually, provide the solution for

- science-based stockpile stewardship and
- accelerator transmutation of waste.

While the present activities in applications will continue, the range of applications will grow in the future. Through our innovative scientists and facilities, the low-energy nuclear science community plays a crucial role in advancing nuclear-related interdisciplinary research and applications whose benefit to our society is vital to its long-term well-being. We must remain diligent in fostering and further advancing such work at our current facilities and we should be forward looking to include these activities when planning future facilities such as RIA.

1.   INTRODUCTION

The nucleus is a unique two-fluid and finite many-body quantal system of fermions interacting under the strong, electromagnetic, and weak interactions. As such, it is an excellent laboratory for the study of both mean field and many-body physics.   The nucleus occupies an intermediate niche between single component systems, such as electron gases, and many-component systems, such as quark-gluon plasmas. Being fermionic, and having low degeneracy states, it is therefore especially sensitive to the interplay of single particle and collective behavior as dictated by the Pauli Principle.

Nuclear structure physics focuses on the diverse and rare phenomena of the nucleus by probing the characteristic single-particle and collective modes of excitation. In the nuclear system, the number of active bodies can be precisely varied in a controlled fashion. (Indeed, with the advent of exotic beam facilities, the ability to do this is greatly enhanced.) Therefore, it is possible to study nuclear modes and nucleonic correlations and their evolution with particle number in unique ways, with applications to other mesoscopic systems in atomic and condensed matter physics. Pairing in nuclei is, for example, relevant to other superconducting systems while the two-fluid, proton-neutron aspect adds an extra dimension. The evolution of structure with excitation energy in nuclei allows study of the general problem of the transition from order to chaos. Studies of isomers and shape coexisting structures, including superdeformations, provide insights about symmetry scars (highly excited states with well defined quantum numbers representing order in chaos). Exotic nuclei far from the valley of beta stability offer the possibility to study weakly bound quantal systems, quantum mechanical tunneling, and the coupling to the particle continuum. Neutron rich nuclei exhibit entirely new forms of matter (low density, spatially extended, superconducting matter) that also has relevance for neutron stars. By analyzing variety of nuclear behaviors, nuclear theory aims to develop a unified microscopic description of the nucleus.

Nuclear astrophysics is concerned with the influence and impact of microscopic nuclear structure and nuclear reaction physics on the development and evolution of stars as macroscopic systems in our Universe. Reactions of nuclei control the energy generation in stars, the luminosities with which we are able to observe their existence, and represent the engine of stellar evolution. Nuclear reactions determine the production of all of the observed elements through the evolution of the Cosmos. In the past century, astrophysical research was strongly guided by atomic physics, which provided the spectroscopic tools required for the study of stellar atmospheres. Now nuclear astrophysics is becoming the unique tool for monitoring the physics processes in the core and in the deeper layers of stars and stellar explosions.

Section 2 will identify the "burning" scientific questions in nuclear structure, nuclear dynamics, and nuclear astrophysics along with their potential significance in nuclear physics and of astrophysics. It will summarize the achievements of these sub-fields over the last decades and will identify the scientific and technical challenges and goals these communities will have to face in the near and long-range future. In a separate section 3 the situation on infrastructure and manpower resources will be discussed. A specific

aspect of the field is the wide range of applications from art to archaeology, from material science to geo-science, in forensic studies to defense related issues, and finally as a unique tool in medical diagnostics and medical treatment. These aspects will be highlighted in section 4. In section 5 we will to summarize the international programs and present goals in nuclear structure and nuclear astrophysics, which compete and complement the US efforts in these fields. We conclude in section 6 with a summary and the recommendations.

2. SCIENCE ASPECTS IN NUCLEAR STRUCTURE AND NUCLEAR ASTROPHYSICS

The scientific questions in nuclear structure, nuclear dynamics and nuclear astrophysics are closely interlinked. In the following we present the broad range of scientific questions and problems in both fields covering the experimental as well as theoretical point of view.

The long-range perspectives in nuclear structure and nuclear astrophysics, in the context of the whole nuclear science, have recently been summarized and reviewed by the National Research Council report "Nuclear Physics, The Core of Matter, The Fuel of Stars" (http://www.nap.edu/html/nucphys/pdf.html). In addition, there have been a series of White Papers published over the last two years with the goal to identify and define the relevant questions in nuclear structure physics and nuclear astrophysics with stable and radioactive beams. In particular we refer to the series of white papers resulting from recent workshops in Columbus OH in June 1998, "Scientific Opportunities with an Advanced ISOL Facility" (http://www.er.doe.gov/production/henp/isolpaper.pdf), the MSU white paper "Scientific Opportunities with fast Fragmentation Beams from the Rare Isotope Accelerator" (http://www.nscl.msu.edu/research/ria/whitepaper.pdf), and finally the white paper on "RIA Physics" (http://www.nscl.msu.edu/conferences/riaws00/ria-whitepaper-2000.pdf) where the broad range of rare ion beam applications and opportunities is discussed in considerable detail. The third white paper summarized the results of the recent RIA workshop at Durham, NC, in June 2000, to which reference is encouraged. Our discussion of exotic nuclei in parts of the text below only addresses a few key topics.

Nuclear astrophysics focuses on the quest for the relevance and impact of nuclear structure and reaction processes for stellar conditions while the stellar conditions define the energy range for these processes. A broad summary of the present questions and problems in Nuclear Astrophysics is given in the white Paper on "Opportunities in Nuclear Astrophysics" (http://www.nd.edu/~nsl/kn/whitep.pdf), which summarizes the results of the town meeting on nuclear astrophysics at Notre Dame, IN, in June 1999.

Because the scientific case has been discussed at such detail before, we present here only a short summary of the goals and aspects of nuclear structure and dynamics and nuclear astrophysics. The following sections are based on the reports from the different working groups from the DNP town meeting on Nuclear Structure and Nuclear Astrophysics at Oakland, CA in November 2000.

2.1 Achievements and Goals in Nuclear Structure and Reaction Physics

The main goal of nuclear physics is to explore the nature of strongly interacting matter. This can entail the study of QCD and the interactions of quarks and gluons. It can also

entail the quark gluon structure of the nucleon and the origin of nucleon-nucleon (NN) forces. At the nucleonic level and in the nucleus itself, it entails the structure, topologies, and excitation modes of nuclei, and the understanding of these interactions between the nucleons. Another concern is the dependence of those interactions and structure on nuclear density, excitation energy or temperature, angular momentum, and isospin. The latter dependence has its signatures in the structure of exotic nuclei and has been identified in recent years as the essential crucible for obtaining a deeper, more comprehensive, understanding of the nucleus and of the underlying nuclear Hamiltonian. Technological advances in accelerator and ion source/target technology, and in detector systems, now allow us to study a much wider panorama of the nuclear landscape than ever before (see Fig. 1) and, in particular, to probe the response of nuclear systems to proton-neutron asymmetry. Research in new areas of the nuclear chart will explore the very limits of nuclear binding, the properties of loosely bound quantal systems, the interplay of collective and single particle degrees of freedom, and the evolution of structure. It will utilize the enhanced 'gene' pool of accessible nuclei to isolate and amplify particular facets of nuclear behavior and of nucleonic interactions. The ultimate goal is a comprehensive unified understanding of the atomic nucleus in all its manifestations and richness. Construction of RIA is essential to the pursuit of this goal.

Current exotic beam facilities have started to give us glimpses of the uncharted territory that lies ahead. Highly efficient gamma-ray arrays, such as GAMMASPHERE, in combination with auxiliary devices, have allowed the study of new phenomena with very small cross-sections. With high-resolution fragment separators, like the FMA at Argonne or the RMS at Oak Ridge, it is now possible to study nuclei near the proton-drip-line. Coupling gamma-ray arrays with these separators and exploiting the recoil decay tagging technique has pushed structure studies to very exotic nuclei. In addition to providing glimpses of new physics in proton-neutron asymmetric media, these studies have also given us important new nuclear structure and reaction data of value to nuclear astrophysics, which we will discuss in more detail in the following section. Crucial to understanding the nucleus are advances in our theoretical approaches. The last few years have seen major progress in theory in a number of areas. This includes ab-initio calculations of light nuclei, the development of new and better effective interactions, the extension of theoretical methods to loosely bound systems incorporating the continuum of positive energy states, advances in shell-model methodology, and the discernment of new symmetries in collective models.

There have been significant developments in the characterization of the bare nucleon-nucleon force and in ab-initio calculations of very light nuclei. The importance of multi-nucleon forces and current operators in nuclear systems has been clearly established. With the Green's function Monte Carlo methods, theory was able to calculate ground and low-lying excited states for nuclei up to A=10; no-core shell model calculations are now possible for all p-shell nuclei. These calculations have demonstrated that collective and single-particle nuclear structure does in fact arise from the bare nucleon forces that explain NN scattering and properties of three-body systems. In the near future, various ab-initio calculations will extend their reach to ^{16}O. The theoretical understanding of heavier nuclei, which cannot be treated by ab-initio calculations, has also made
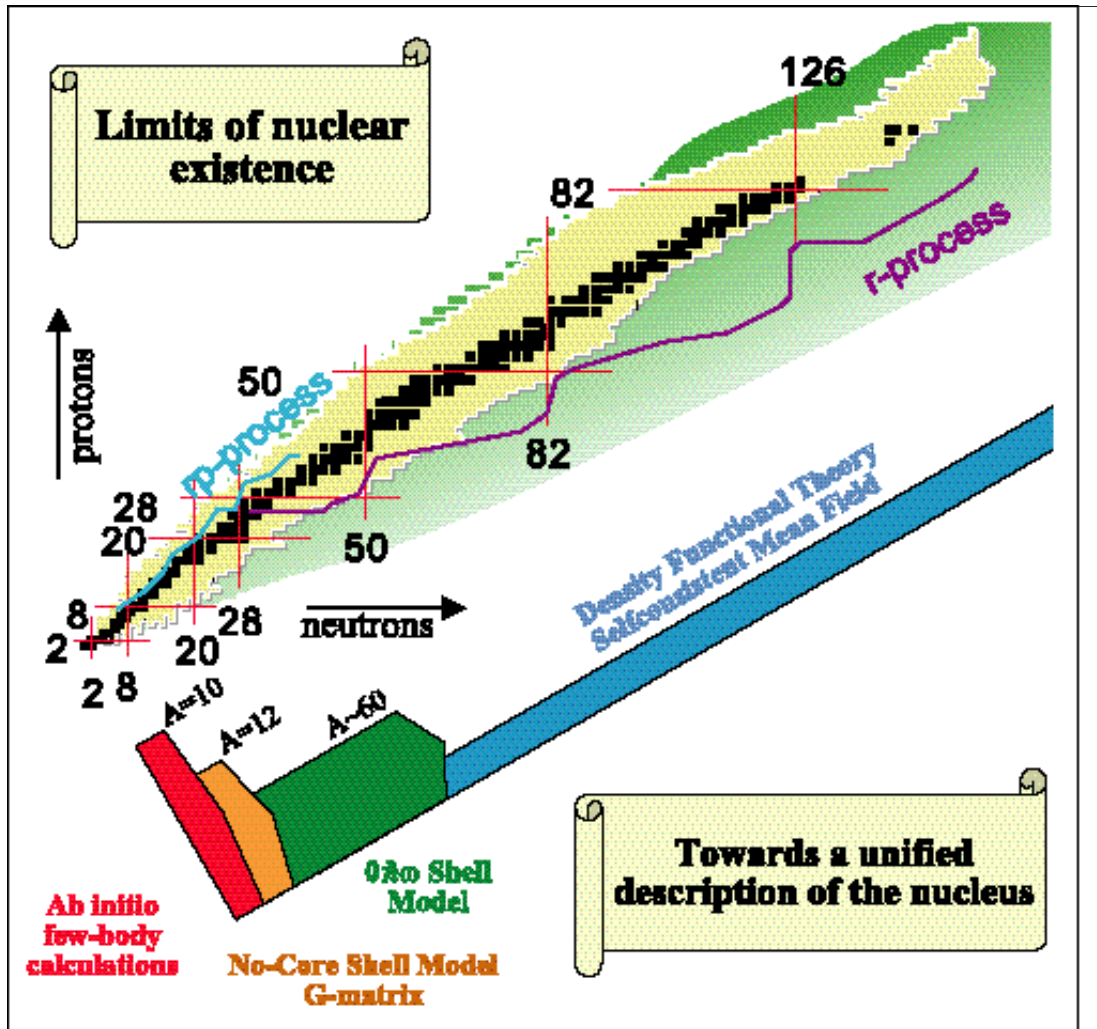
Figure 1: Top: the nuclear landscape. The black squares represent the stable nuclei and the nuclei with half-lives comparable to or longer than the age of the Earth (4.5 billion years). These nuclei form the "valley of stability". The yellow region indicates shorter-lived nuclei that have been produced and studied in laboratories. The drip-lines represent the limits of particle stability. Many thousands of radioactive nuclei with very small or very large N/Z ratios near the drip-lines are yet to be explored. In the (N,Z) landscape, they form the terra incognita indicated in green. The proton drip line is already relatively well delineated experimentally up to Z=83. In contrast, the neutron drip line is considerably further from the valley of stability and harder to approach and is estimated through nuclear model predictions. The red vertical and horizontal lines show the magic numbers around the valley of stability. The anticipated paths of astrophysical processes (r-process, purple line; rp-process, turquoise line) are shown. Bottom: various theoretical approaches to the nuclear many-body problem. For the lightest nuclei, ab initio calculations (Green's Function Monte Carlo, no-core shell model) based on the bare nucleon-nucleon interaction, are possible, while medium-mass nuclei are treated by the large-scale shell model. For heavy nuclei, the density functional theory (based on selfconsistent mean field) is the tool of choice. Investigating the intersections between these theoretical strategies aims at the development of a unified description of the nucleus.

significant advances in recent years. A key goal is the derivation of appropriate effective interactions and operators from the bare NN forces and currents. Advances in shell model diagonalization and Monte Carlo studies made it possible to reach the fp-shell and neutron-rich nuclei such as Mg and Ne, as well as iron and nickel nuclei. Enormous progress has been made using density-functional mean field theories, including both relativistic and non-relativistic formulations. Indeed, research in this area, including the density dependence of effective interactions, the consequences of weak binding, and coupling to the continuum, has been a prime motivating factor in our understanding of the physics of exotic nuclei, illustrating the benefits of a strong symbiosis between theory and experiment. Complementary to these microscopic approaches, advances have also been made with models that explicitly exploit the dynamical symmetries of the many-body Hamiltonian. These developments will be discussed in more detail in the section on nuclear theory.

2.1.1   Studies of Nuclei Near Stability

The understanding of collective and single-particle aspects of nuclei has been a central theme since the early days of nuclear physics. It is of fundamental importance to understand the microscopic origin and interplay of these degrees of freedom, which are intimately related to the correlations exhibited by nuclei and to the evolution of nuclear structure with N and Z, with energy, and with angular momentum. This defines the main directions of nuclear structure studies at and near stability over the last decade and into the future:

- to study the single-particle motion in the nucleonic medium,
- to explore the nuclear collective modes, including rotations and vibrations,
- to understand the evolution of nuclear structure with proton and neutron number.

Several major achievements and discoveries have been made in this area in recent years, pointing the way to future directions of research. We outline some specific examples of these in the next few paragraphs but, of course, these themes pervade nearly all aspects of the discussion throughout this section.

The study of nuclear shape as a function of angular momentum has long been an intriguing problem. The last years have seen some important progress. With advances in gamma ray resolving power, high spin states have now been studied for the first time in such important double magic nuclei as ^{48}Ca, ^{132}Sn and ^{208}Pb. New regions of superdeformation have been identified. The discoveries in the light mass regions are especially important since they enable us to study these highly collective states in the framework of both interacting shell model and mean-field approaches, and to investigate the microscopic origin of collective rotation. By studying high spin states in such nuclei one can obtain important information about cross-shell excitations that play a crucial role in exotic nuclei far from stability. Finally, there is strong evidence near A=170 for triaxial superdeformed bands that exhibit wobbling motion that has been long searched for.

Evidence that key residual interactions such as pairing are attenuated at high spin has emerged from studies that show that a picture of extreme single particle motion can account for a large variety of high spin behavior. This represents a beautiful example of the application of the shell model at extremes of high angular momentum and deformation.

A new form of quantum rotation has been found in several regions of the nuclear chart. It involves a gradual closing of the angle between angular momentum vectors carried by the neutrons and protons (shears mechanism). Another recent discovery is the possible existence of chiral bands and is intimately related to the existence of rigid gamma deformations. Understanding both modes is important for understanding proton-neutron correlations and isovector modes in nuclei.

The study of transitional nuclei has witnessed some remarkable developments. Recent studies in the Sm isotopes have shown that finite nuclei can exhibit behavior resembling phase transitions. This inspired the derivation of a new class of symmetries or paradigms that give analytic predictions for critical point nuclei, which are perhaps the most challenging since they display intense competition of different degrees of freedom. Examples of first and second order critical point paradigms (X(5) and E(5)) have now been identified empirically. Studies near A=100 hold the best promise for identifying other examples of these new paradigms.

Considering the fact that the frequency of nuclear vibrational motion is comparable to that of the single-particle motion, the mere existence of collective vibrational states in nuclei is astonishing. Multi-phonon states are an issue of considerable importance since their existence relates directly to the interplay of single particle and collective degrees of freedom, and to the influence of the Pauli Principle on collective modes. The search for such states has been recently expanded to include vibrational modes of different multipolarities and proton-neutron symmetries. Recent years brought spectacular examples of nuclear vibrators, including quadrupole and octupole one and two-phonon states in spherical and deformed nuclei. Our present understanding of these vibrational modes in nuclei does point to unique dynamics in nuclei in comparison with other quantal systems.

Systematic measurements of the isoscalar monopole resonance and the isoscalar dipole resonance have significantly narrowed the experimental value of nuclear incompressibility. Studies of the giant spin-dipole resonance have provided important information on neutron radii, and the Gamow-Teller strength studies through charge-exchange reactions have elucidated the role of higher-order correlations and of delta resonances in nuclei.

The idea of supersymmetry (SUSY) in nuclei -- a concept linking the properties of adjacent even-even, even-odd, and odd-odd nuclei – was advanced two decades ago but only partial empirical support was found. Recently, in thorough high-resolution experiments, an extensive data set was obtained in the Au region confirming a large number of SUSY predictions.

2.1.2　　　　　Studies of Exotic Nuclei

Studies of the structure of nuclei at the very limits of stability test the dependence of the strong force on the proton-to-neutron ratio and can reveal wholly new phenomena, nuclear topologies, structure, and excitation modes. This will be the focus of highest interest in the years to come, first with existing exotic beam facilities, especially at the new coupled cyclotron facility at the NSCL, and at the HRIBF, and then later with RIA.

At present, even the question even of which combinations of protons and neutrons form a bound nucleus has not been answered experimentally for most of the nuclear chart. There are three such limits of nuclear stability:

- very heavy elements, where the Coulomb force competes with the strong force,
- very proton-rich nuclei, where a strong Coulomb barrier governs the tunneling of unbound protons,
- neutron-rich isotopes, where large differences in the proton and neutron distributions give rise to new phenomena.

In the following we will discuss the phenomena that we hope to investigate and to reveal by exploring these three limits of stability.

The field of superheavy elements has undergone a renaissance recently, motivated by advances in single-atom detection techniques and the availability of high-current heavy-ion accelerators. Investigations of the heaviest nuclei probe the role of the Coulomb force and its interplay with shell effects in determining the boundaries of the nuclear landscape. Indeed, the heaviest nuclei are different from the other elements in that their binding is predominantly due to quantal shell effects. The major accomplishments in this area in the last few years are, first the discovery of new elements Z=110-112 where α-decay chain links to known nuclei assure correct element identification, the tentative production of Z=114, 116 where assignments are less certain because their decay chains end in as yet unknown regions, and the possible discovery of Z=118 whose existence is still unconfirmed; the second accomplishment was the coupling of the power of GAMMASPHERE with the channel selectivity of the Fragment Mass Analyzer to open up the spectroscopy of the very heaviest elements. Indeed, the first spectroscopy in the Nobelium region, above Z=100, has been achieved, with the remarkable discovery that these deformed nuclei are stable against fission up to angular momentum I=22. The stabilization results from pronounced shell effects whose understanding will influence our predictions of shell stabilization throughout the heaviest nuclei.

Much progress can be expected in the next five years. First, new experiments on elements Z=114-118 have already started while first explorations of higher-Z nuclei will take place soon. These measurements will take advantage of the improved instrumentation and larger beam currents that are now available. First gamma-ray studies of element 103, 104 are also within reach. These experiments will challenge mass models and calculations of fission barriers and provide badly needed tests of the description of the production mechanism itself. First chemistry of elements 108 to 112 will also take place.

In the long-term future, intense, exotic beams from RIA will complement and extend the present program with stable beams in at least two ways. First, they will help delineate the center of shell stabilization in superheavy nuclei through the formation of many new, neutron-rich superheavy nuclei. For example, the fusion of intense beams of neutron-rich Kr isotopes from RIA with ^{208}Pb targets can form isotopes of element 118 calculated in some models to be more stable than the isotope reported thus far. RIA will also make a significant contribution to our firm identification of the new superheavy elements created in fusion reactions with stable beams since neutron-rich beams will allow the creation and study of many of the nuclei which are part of these decay chains, thus putting the identification of superheavy elements on solid experimental footing.

Studies at the proton drip line address a number of fundamental questions. First, establishing the exact location of the drip line represents a stringent test for mass models. In addition, because of the extra stability provided by the Coulomb barrier, it is possible to study quasi-bound states, searching for signs of mixing with continuum states or for possible new correlations, and to examine quantum tunneling through a three-dimensional barrier. Finally, information on the location of the drip line constrains the path of nucleosynthesis in the rp process, which will be discussed in more detail in the next section. A flurry of activity has characterized the last five years in this area. The proton drip line has now been fully mapped up to Z=21 and, for odd-Z nuclei, up to In. In the lightest systems, proton-unbound nuclei like ^{11}N and ^{12}O have been studied as resonances. Between Sn and Pb, many spherical proton emitters have been discovered and the spectroscopic factors characterizing their decay are now understood. Recently, evidence for deformed proton emitters has been found and the deformation has been shown to have a strong impact on the measured half-lives. The recent discovery of a new mode of nuclear decay, the direct two-proton emission from an excited state of ^{18}Ne, will allow us to better understand pairing correlations and nucleonic superconductivity in nuclei. Two-proton decay was predicted decades ago but, until recently, experimental efforts have found only sequential emission of single protons through an intermediate state. One of the remaining key questions is whether the two emitted protons are closely coupled to form ^{2}He, or if they are emitted almost independently in a direct three-body breakup ("democratic" decay). The double-magic nuclei ^{48}Ni and ^{100}Sn have been produced and approached spectroscopically. In this mass range detailed spectroscopic studies with RIA will be necessary to conclusively address the question and possibility of two-proton capture processes, which have been predicted for the rp-process.

In the short-term future, the study of proton-rich nuclei will proceed vigorously. The search for particle-stable nuclei at or near the proton drip line with Z>50 will continue, focusing mostly on regions where calculations predict the onset of deformation. In particular, the region above ^{208}Pb, where the Coulomb field is the strongest, remains largely unexplored. The possibility to study proton emitters and beta-delayed proton emitters in lighter nuclei (Z<50) will improve significantly and will allow in particular to study rp-process nuclei near the N=Z line.
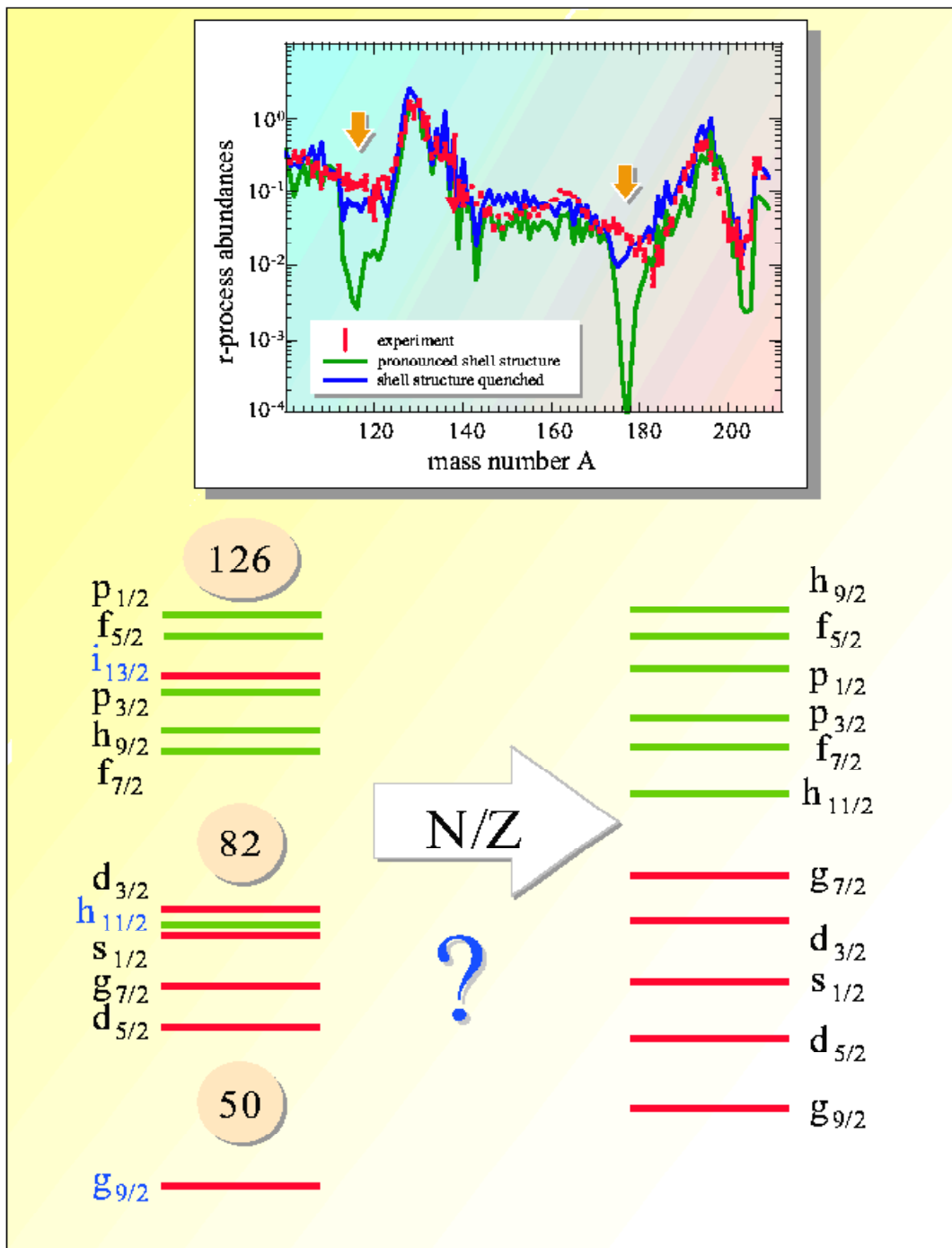
Figure 2: Left: Spherical shell structure characteristic of nuclei close to the valley of stability. The nuclear shells are separated by magic gaps. Right: Neutron shell structure predicted for neutron-rich nuclei, corresponding to a shallow mean-field potential and significantly reduced spin-orbit coupling. The very neutron rich drip line nuclei cannot be reached experimentally under present laboratory conditions. On the other hand, these systems are the building blocks of the astrophysical r-process; their separation energies, decay rates, and neutron capture cross sections are the basic quantities determining the results of nuclear reaction network calculations. The properties of very neutron-rich nuclei are linked to the r-process abundances, shown in the inset. The red squares indicate the observational r-process abundances for nuclear masses greater than A=100. The theoretical abundances, marked by green and blue, were obtained in r-process network calculations. They are based on microscopic mass formulae, which neglect quenching (green curve) or assume quenching of the spherical shell gaps towards the neutron drip line (blue curve). The calculations that incorporate a quenching of magic gaps at N=82 and N=126 seem to improve our ability to understand the experimental solar abundances of the elements around A=118, 178, and above 200.

Longer-term progress will depend on the availability of the high-intensity beams from RIA. With this facility the task of delineating the proton drip line in odd-Z nuclei will be completed. Also, we will be able to study in detail collective motions in these weakly bound systems via Coulomb excitation techniques.

The study of neutron-rich nuclei opens up wholly new areas of nuclear physics. This side of stability offers the greatest likelihood of major discoveries in the future. Indeed, it has already yielded a rich harvest of new phenomena and results at present facilities. The neutron-rich nuclei can provide a unique terrestrial laboratory to study the properties of neutron matter. Their study also has profound implications for our understanding of the r-process and of the violent stellar events that spawn it, as we will see in a later section. The fact that the limit of nuclear existence for neutron-rich nuclei is experimentally unknown for all but the lightest eight elements illustrates both the experimental difficulty in accessing neutron-rich nuclei and the vast promise of new and planned accelerator facilities. Further mapping of the limits of existence of n-rich nuclei will help us understand better the nature of the mean field and of residual interactions in exotic, loosely bound nuclei.

The valence neutrons of some of the most neutron-rich light nuclei can have density distributions that extend far beyond the nuclear core. The low binding energy yields extended and diffuse neutron matter distributions for which surface effects and coupling to the particle continuum become very influential. Two-neutron halo nuclei (such as ^{11}Li) are providing insight into a new topology in nature with a so-called "Borromean" property, where each two-body sub-system of the stable three-body system is unstable. In heavier nuclei, one expects an outer zone of neutron matter, a neutron skin. The nuclear physics in this region should be exotic and new since virtually nothing is known about such nuclei.

The weak binding inherent to nuclei at the drip lines has a profound influence on nuclear properties. Strongly affected will be the underlying shell structure, which responds to the presence of weakly bound states and of diffuse matter. In addition to changes in the radial behavior of the mean field potential we expect that the spin-orbit force, which is crucially important for the determination of the magic shell closures, will decrease near the neutron drip line. Recent calculations indicate that, near the neutron drip line, one may encounter a quenched neutron shell structure with dramatically reduced shell gaps, possibly re-ordered orbitals and/or the emergence of new magic numbers (see Fig. 2).

In addition to changes in the nuclear mean field, residual interactions are likely to evolve near the neutron drip line, possibly gaining in importance. For example, pairing is expected to take on increased importance as the continuum provides an abundance of possible states for pair scattering. Moreover, other forms of nucleonic correlations or aggregations within the skin may develop. The strong pairing, quenched shell structure and the different density distribution for neutron and proton will have a profound effect on nuclear deformation and rotational properties. Thus even the traditional concept of single particle motion in a mean field may lose validity. Possibilities such as clustering of the neutrons within the skin need to be contemplated (they will likely give rise to new,

low-lying collective modes) and the nature of the correlations between the core and the skin need to be explored.

Within the next five years the limits of existence for neutron-rich nuclei will be established for all elements lighter than sulfur (Z=16). This will double the number of elements for which the neutron drip line has been determined experimentally. This will also end the ten-year long quest to advance by one element from oxygen to fluorine. Besides establishing the neutron drip line, measurements of nuclear masses away from stability will take center stage as they represent first stringent tests of relevant nuclear models. Such measurements also provide first indications for new regions of collectivity or for new shell closures. Extended nuclear halo systems, and experiments searching for predicted new modes of collective excitation, such as the soft dipole resonance mode, will be carried out. Furthermore, additional waiting point nuclei on the r-process path will become accessible. Fusion reactions and Coulomb excitation will allow continuing explorations of neutron-rich nuclei.

The long-term future in the study of neutron-rich nuclei is again linked to the availability of RIA. RIA will establish the limits of nuclear existence for elements up to manganese (Z=25), and, depending on the exact location of the neutron drip line, perhaps all the way up to zirconium (Z=40). For heavier nuclei, RIA will establish nuclear existence and binding along isotopic chains 10 to 20 neutrons beyond the heaviest nucleus identified to date. This will provide the stringent constraints required for more accurate predictions/extrapolations of the location of the neutron drip line. With its extended reach for neutron-rich exotic beams, RIA will also determine fundamental nuclear properties such as mass, radius, and shape, providing additional experimental signatures to test theoretical descriptions of neutron-rich nuclei, and to probe neutron-rich nuclei along the path of the astrophysical r-process.

The intensities provided by RIA ensure that halo nuclei in the vicinity of the drip line will be accessible to experiment, not only up to mass A~50 where first theoretical predictions exist (^{34}Ne, ^{42}Mg, ^{44,46}Si, ...), but also for nuclei with mass A closer to ~100, where the presence of such structures is a matter of much theoretical debate. RIA beams will also provide the necessary tools to study nuclei with possible skin topologies. For example, the onset of the skin and its dependence on neutron number, as well as structural evolution, single particle structure and collective modes will be investigated by studying a small number of selected isotopic chains where large differences in N/Z ratios will be available. The nuclei in the Zn, Kr or Zr chains are good candidates for such studies. At RIA nuclei as neutron rich as ^{90}Zn, ^{108}Kr and ^{122}Zr (with 20, 22 and 24 neutrons more than the heaviest stable isotope in the respective chains) will be available at the 0.01/s level where experiments have already been demonstrated to be feasible.

In order to accurately evaluate possible alterations to shell structure, it is important to determine the latter structure in the first place. At present, our knowledge is based mostly on the properties of the single-particle levels of a few nuclei located near good closed-shells. In heavy nuclei, by far the best information comes from the immediate vicinity of ^{208}Pb. A unique opportunity to improve this situation exists with RIA, especially in the

neutron-rich sector. Intense beams of the neutron-rich, double-magic [132]Sn nucleus will be produced. Beams of recently discovered double-magic [78]Ni and semi-closed shell nucleus [60]Ca will be available as well at usable intensities. In addition, beams of exotic nuclei with one or two particles or holes outside these magic nuclei will be available with comparable yields. Hence, essential information about single particle states, about the occupation of these states by nucleons, and about the interactions between these nucleons will be obtained with RIA.

The dependence of energy on density and/or temperature is fundamental to the description of any fluid. In the case of atomic nuclei, the search for the nuclear equation of state (EOS) is motivated by many unique aspects of the physics of these systems, especially the fact that nuclei can be considered as two-fluid quantal droplets. Small amplitude modes are nearly harmonic density oscillations about the stable minimum at ρ_o ~ 0.16 nucleons/fm^3. For density variations in the vicinity of ρ_o the nuclear EOS can be explored through the excitation of the isoscalar monopole (ISMGR) and dipole (ISDGR) resonances. One of the near-term future goals of our field is to achieve a consistency between the results from ISMGR and ISGDR. The interference between nuclear and Coulomb excitation of the isoscalar resonances with particles gives information on the differences between proton and neutron density profiles. This technique gains power farther from β-stability. The behavior of nuclei excited to large-scale density fluctuation depends on whether the equation of state is "soft" or "hard" with respect to density variations as well as "soft" or "hard" with respect to isospin variations if the matter is asymmetric. Significant limits have been placed most recently on the EOS at supranormal densities $\rho > 2\rho_o$. These limits were made possible by the extension of flow measurements to higher beam energies and by the discovery of a transition to in-plane elliptic flow.

Extracting the isospin dependence of the EOS will be a major effort in the near future. This is one of the least understood properties of nuclear matter as evidenced by the divergent predictions of modern microscopic theory. As the energy density depends, in the lowest order, quadratically on isospin asymmetry, beams and targets covering a wide range of asymmetry are required. As the sensitivity of these observables grows with increasing asymmetry this work requires the use of the new facilities capable of producing nuclei far from stability with energies above $E/A \equiv 100\text{-}200$ MeV.

In the low-density regime of nuclei at high excitation energies, a bifurcation below a "critical" temperature leads to the appearance of two phases, liquid and gaseous. As the system enters this region, it eventually becomes mechanically unstable as it breaks up into liquid droplets embedded in a vapor. The very coexistence of the liquid and gas phases implies clusterization. Due to the two-component nature of the nuclear fluid a nontrivial equilibrium component-partition is expected between the higher density (liquid-like) regions and the lower density, vapor-like or surfaces, regions. From the experimental side, in the area of low-density nuclear matter and cluster formation, important scaling laws have been discovered governing the cluster production. These laws describe the fragment multiplicity distributions and the changes in isotope yields with the system isospin asymmetry. The isospin degree of freedom should be exploited

experimentally to deduce the relation between the production of clusters and the liquid-gas phase transition of nuclear matter.

To conclude, in all these areas of study, those relating to single particle and collective modes in nuclei, to the limits of nuclear existence, to the properties and topologies of exotic nuclei and to the behavior of nuclear matter under density oscillations, great advances have been made in the last five years, major progress is expected from existing facilities in the next five years, and the critical need for the future is access to new realms of exotic nuclei far from stability.

First and foremost, the keys to progress in this field are the continued exploitation of existing stable and radioactive beam facilities critical to pursuit of the exciting initiatives and physics themes currently under study and the training of new scientists for work in this field when RIA comes on line. Longer term progress rests on the construction of RIA as soon as possible. Concurrent advances in instrumentation, such as gamma-ray tracking arrays is also necessary to provide essential tools for the future. Finally, enhanced support for nuclear structure theory is essential for the vitality of the field, for developing new concepts and computational approaches, and for interpreting what will surely be much fascinating and unexpected data in the years to come.

2.1.3   Nuclear Structure Theory

The nucleus is a fascinating quantum mechanical system exhibiting diverse and rare phenomena. Governed by the strong interactions between nucleons, nuclei exhibit strong correlations resulting in both single-particle and collective modes of excitation; examples of the latter include Goldstone modes like rotation and tunneling between spherical and deformed intrinsic nuclear configurations. Nuclear theory attempts to understand these excitations and the response of nuclei to diverse external probes within a coherent framework. This framework must encompass a wide range of energy and momentum scales for nuclei ranging from the deuteron to the superheavy elements. Nuclear theorists strive to describe the structure and dynamics of these, often disparate systems, and to apply our knowledge of these systems to help unravel mysteries of our Universe. This section will concentrate on nuclear structure and dynamics; the astrophysics context will be discussed in the following section.

Many nuclear structure efforts begin with a description of interacting nucleons and associated currents coupling to external probes. This starting point poses fundamental questions for the field. How does such an effective theory arise as a reasonable approximation to QCD, and what determines its range of validity? In recent years techniques based on chiral symmetry have provided some answers to the first question, producing effective theories similar to classical nuclear physics with dominant two-body interactions, controlled expansions in relativity, etc. Facilities like JLab are helping with the second question, testing the predictions of both classical (e.g., nuclear model) and QCD (e.g., scaling according to asymptotic quark counting rules) calculations over momentum ranges where the validity of neither is clear. A long-term hope is that some

nonperturbative QCD technique, such as lattice QCD, will match onto our classical theory at such an intermediate scale, thereby determining the low-energy parameters of nuclear interactions from QCD.

Important questions remain open within the picture of the nucleus as interacting nucleons. We need to understand the foundations of independent particle motion: How does shell structure evolve in this strongly interacting system? What is the role of the continuum in weakly bound nuclei and their reactions? How do nuclei respond to external electroweak probes, how can precise predictions be made for low-energy reactions important for astrophysical purposes? To construct a coherent picture of the nucleus, we would like to understand the transition from light to heavy systems. While for few-body systems precise calculations are possible, for heavy systems, because of their complexity, various approximations (including truncation schemes) must be invoked. Can a simple picture of effective interactions and operators evolve from this physics, and what are its crucial features? How does this picture change with density and isospin?

Collective degrees of freedom dominate many aspects of nuclear structure: despite the complexity of the underlying quantum mechanics, nuclear responses often exhibit a simplicity associated with either single-particle modes or collective modes such as rotation and vibration. What are relevant degrees of freedom of the nuclear many-body system? How does collectivity arise from the underlying Hamiltonian? What is the microscopic mechanism behind large-amplitude collective motion such as fission or shape coexistence?

Experiments continue to expand the range of known nuclei, with systems far from the valley of stability being an outstanding example. What is the mechanism of binding of exotic nuclei? Are neutron skins clustered? What are the soft modes of excitation and what is the role of correlations in the low-density nuclear zone?

Finally, many important applications of nuclear structure to fields like astrophysics require results of known and greater accuracy. Can we quantify nuclear structure uncertainties in big bang nucleosynthesis and in solar neutrino cross sections? What level of accuracy can be guaranteed in predicting properties of exotic nuclei important to the r-process?

Investigations that try to answer these and other questions are currently underway in the field and significant advances have been made in the last five years. These include: ab-initio Greens Function Monte Carlo calculations for nuclei up to A=10; ab-initio three-body calculations of d+p scattering reactions and low-energy four-nucleon reactions; ab-initio shell-model calculations based on bare NN interactions and insights on effective interactions from effective field theory; applications of Monte Carlo techniques to the nuclear shell model and computational advances in the conventional shell model; microscopic studies of short-range correlations; continuum shell-model descriptions of light nuclei; calculations of stellar weak interaction rates; shell-model descriptions of collective states in medium mass-nuclei; shell-model calculations at the interface between

shells; the prediction that neutrino opacities in nuclear matter are much less than previously modeled; the construction of the self-consistent mass table; investigations of the role of weak binding and pairing in nuclei near the drip-lines using Hartree-Fock-Bogoliubov theory; the discovery of the origin of pseudospin symmetry from the Dirac equation; increased understanding of global features of nuclear collective structure and of the properties of nuclei in the vicinity of shape transitions; self-consistent descriptions of rotational structures in medium-mass and heavy nuclei; time-dependent relativistic mean-field calculations for giant and double-giant resonances; predictions for the structure of superheavy elements. In addition to these nuclear specific applications, work was initiated in other fields. Specific examples include investigations of robust observables given random interactions, explanations of odd-even staggering of masses in nuclei, clusters, and grains; structure calculations of mesoscopic systems such as clusters, quantum dots, and nanowires. Collaborations have also yielded advances in the study of strongly interacting quantum spin systems. In many instances, algorithmic developments and the use of large-scale computational power lie at the heart of these advances.

In view of this progress, we are poised to face several important challenges during the next five years. The experimental emphasis on nuclei far from the valley of β-stability requires us to expand our current exploration of nuclear forces and currents, effective interactions, and techniques to solve the nuclear many-body problem. Significant advances in nuclear theory are required to successfully describe weakly bound nuclei that will be investigated by RIA. Understanding the properties of neutrinos by using nuclei as a probe requires a detailed understanding of the nuclear structure of a given detector material. Many nuclear systems (including nuclear matter) cannot be probed in the laboratory but are very important in astrophysical environments; therefore, reliable theoretical tools must be developed in order to describe these systems.

The Hamiltonian required to describe the structure of nuclei is not known a priori. There exists a great need to determine the Hamiltonian and the relationships between different approaches to nuclear many-body theory. Major progress has been made over the last five years along several lines.

One line involves the use of bare nonrelativistic two- and three-nucleon interactions in the Schrödinger equation. This approach can be implemented essentially exactly for relatively light nuclei using Monte Carlo methods. The two-body forces are fit to nucleon-nucleon scattering data. Three-body forces include terms whose strengths must be determined by investigating three-nucleon scattering and the isospin dependence of nuclear spectra and ground states. Our understanding of three-body forces is still primitive: the most general three-body potential is far more complicated than anything in current use. During the last five years, direct application of these forces to the nuclear many-body problem has shown that nuclear structure indeed develops from the underlying nucleon-nucleon and three-nucleon forces. Currents calculated in this framework yield important information on the electromagnetic response of the light nuclei. During the next five years both technical and theoretical advances in these studies should allow for nearly exact calculations of low-energy scattering and reactions, many important in an astrophysical context, up to A=12. Dramatic advances may be possible in

the next five years, using related methods incorporating Auxiliary-Field Monte Carlo sampling of the nucleon's spins and isospins, to study the mass 16-40 region, as well as dense nuclear matter.

A second approach, focusing on light nuclei, involves the use of effective field theory. This approach is based on the equivalence, at sufficiently low energies, of an effective theory to QCD, provided the former respects the underlying symmetries (chiral, Lorentz) of QCD. The parameters of the low-energy theory, which in principle are determined by QCD, are fixed in practice by matching experiment. Once this is done, other predictions are model independent up to the order (the expansion is in a momentum scale) of neglected higher terms. During the last five years significant progress has been made in studying the deuteron and three-body nuclei in this approach. For example, $n+p\rightarrow d+\gamma$ reaction cross sections as well as $d+\gamma$ breakup were recently calculated within this framework. Major challenges for the next five years include resolving some conflicting "power counting" schemes, defining an efficient theory with pions for the three-body problem, extensions to the four-body problem, and applications to nuclear matter.

A third approach involves the use of an effective Hamiltonian within a restricted model space. This effective interaction can in principle be derived from the bare interaction through the use of renormalization theory. Shell model techniques can then be applied to this effective Hamiltonian to define the structure of the nucleus of interest. Other operators can likewise be renormalized for use in the chosen model space, although further research in this direction is clearly needed. This shell model approach has been applied to the description of moderately heavy nuclei that are not too far from closed shells. Major computational advances, both in the traditional shell model methodology and in the use of Monte Carlo methods, have extended the region of applicability of these methods dramatically over the last five years. Further progress that extends the shell model methodology to even heavier nuclei is an important goal for the next five years.

The shell model approach in light nuclei has been extended, primarily during the last five years. As in heavier systems, the calculations are carried out using an effective Hamiltonian derived from the bare force. However, in these calculations no inert core is assumed and all A nucleons are considered as active. These calculations have now pushed into the p-shell. Very recent work that applies effective field theory techniques to the determination of the effective interaction in a given model space also shows great promise for light nuclei. This work may provide important guidance to phenomenological efforts to construct effective interactions in heavy nuclei, where the model space truncations are often far more complex.

Self-consistent mean-field theories offer the fourth microscopic approach to nuclear structure and here too an appropriate effective many-body Hamiltonian is necessary input. In these approaches, one defines an energy density functional and solves for ground state and bulk properties of a given nucleus, as well as for collective nuclear excitations. Both relativistic and nonrelativistic approaches have seen progress in the last five years. The effective Hamiltonians in this approach are typically parameterized, with the parameters obtained from global fits to nuclear properties. While new data on exotic

nuclei from RIA will permit the parameters of these effective Hamiltonians to be more accurately determined, it is crucial to tie the modern energy density functional to the microscopic Hamiltonians. Further extensions of the self-consistent theory to include new correlations such as proton-neutron pairing and to restore internally broken symmetries are important challenges for the future.

By exploring the connections between these approaches, nuclear theory aims to develop a coherent description of the nucleus. In order to pursue this goal, adequate tools are needed. All of the above microscopic approaches to the structure of nuclei have benefited significantly from recent increases in computational power and associated algorithm development. Access to, and the use of, national computing facilities remains an important ingredient in nuclear theory research. Continued access to the most advanced computing facilities is vital to all areas of nuclear theory, and in particular is crucial for nuclear many-body theory.

Complementary to these microscopic approaches, major advances have also been made with models that focus more directly on the collective building blocks of nuclear structure. Continued work on these more phenomenological models - often based on symmetry considerations - is called for, especially as regards their link to the underlying forces at play in the nucleus. It still remains a major challenge for nuclear theory to understand microscopically these simple models and underlying coupling schemes.

2.2   Achievements and Goals in Nuclear Astrophysics

Nuclear astrophysics is one of the forefront applications of nuclear physics. It is concerned with the domineering impact of the microscopic aspects in nuclear structure and nuclear reaction physics on the macroscopic phenomena we observe in our universe. Nuclear Physics aspects set the conditions for the evolution of our universe within the first three minutes of the Big Bang. The characteristics of few particle systems such as the mass of the deuteron determined the onset of the formation of elements. The particle instability of mass 5 and mass 8 systems prevented the instantaneous formation of all the heavier elements beyond Boron and postponed its nucleosynthesis to the formation and evolution of stars.

The stellar evolution is directly correlated to its nuclear fuel. Hydrogen induced reactions drive the energy generation in main-sequence and early red-giant stars, Helium induced processes govern the evolution late in the red-giant phase, and heavy ion fusion and photon induced fission processes characterize the final span of stellar life. Fast convection and dredge-up processes spill the reaction products to the stellar atmosphere where they mix with the interstellar dust through solar wind driven mass losses and the formation of planetary nebulae. Weak and neutrino interaction processes are closely associated with the physics of core collapse type II supernovae; they control the collapse phase itself and originate the neutrino flux that revitalizes the stalled shock which drives the supernova explosion mechanism. Neutrinos therefore are considered to be the unique

signature for the nature of the supernova ignition process. Strong interaction processes, on the other hand, characterize the nucleosynthesis in the shock front through the outer layers of the pre-supernovae star. The neutron-rich gas near the core is thought to be the site of the r-process, which produces roughly half of the elements heavier than iron. All the nucleosynthesis processes in the shock front determine the abundance distribution in the ejecta and cause in particular the production of short-lived radioactive nuclei that power the characteristic light curve of supernova events.

Stellar remnants that accrete mass from nearby companions can briefly flare back to life. Proton and alpha induced fusion processes far off stability drive the thermonuclear explosions on the surface of accreting white dwarf stars or neutron stars observed by astronomers as novae or X-ray-bursts. More spectacular sites of rapid burning can be found in the accretion disks of black holes or in merging neutron stars.

New insight into the nature and characteristics of stars and stellar explosions is a direct result of the rapidly increasing amount of observational data from ground and satellite-based observatories, operating over the entire range of the electromagnetic spectrum. Recent observations by the HUBBLE telescope revealed new aspects of the formation of planetary nebulae from red giant stars, providing a detailed look at the late phases in the evolution of intermediate-mass stars. Peculiar abundance distributions in the nebulae are the signatures of the latter stages of nucleosynthesis. A wealth of information about nucleosynthesis is carried in the abundance patterns observed in meteoritic grains which are condensed in the winds of evolved stars. Observations of old stars by the HUBBLE and the Keck telescopes yield evidence that the r-process abundance distribution observed in the solar system is a general feature throughout the galaxy and throughout stellar evolution. This provides an important constraint on the age of the galaxy. Observations of elemental and isotopic abundances in the oldest stars in our galaxy have challenged our basic understanding of stellar structure and evolution. The new CHANDRA X-ray observatory has shown evidence of the freshly formed isotopes in the material ejected from novae (see fig. 3). Other satellite-based X-ray telescopes reveal new indications for thermonuclear explosions in X-ray bursts and X-ray pulsars. Gravitational-wave detectors like LIGO will be used to probe the details of the explosion and the evolvement of nuclear matter at extreme densities on the surface of neutron stars. Observations of galactic radioactivity by the recently decommissioned Compton Gamma-Ray (CGR) Observatory have provided information about massive stars and supernovae, which could ultimately have impact on our description of the chemical evolution of the galaxy. The new INTEGRAL gamma observatory will multiply the number of observed sources and will strengthen our understanding of nucleosynthesis far from the lines of stability in stellar explosions.

While the observational evidence has multiplied over the last decade, our deeper understanding of the nature of these explosive events and the origin of the observed signatures is still in its infancy. The theoretical models are still rather crude and are often based on global assumptions. Better and more detailed microscopic input parameters are clearly needed to compare the observations with model predictions and to come to a better understanding of the nature of these events. We therefore need to simulate stellar

processes and the associated nucleosynthesis in the laboratory to improve our understanding of these events and to interpret the wealth of observational data. Such experimental simulation of stellar conditions in the laboratory is the crucial link for interpreting the wealth of observational elemental and isotopic abundances data from observatories through complex computer simulation of stellar evolution and stellar explosion. Two major goals have crystallized over the last decade. The first centers on the understanding of nuclear processes far off stability in the rapid rp- and r-process, which characterize nucleosynthesis in novae, X-ray bursts, and supernovae. The second goal focuses on understanding nuclear burning through the different phases of stellar evolution, determining the lifespan of the stars and the ignition conditions of stellar explosions. They also determine the elemental and isotopic abundances observed in stellar atmospheres and in the meteoritic inclusions.

2.2.1 Nuclear physics of stellar explosions

In studies of stellar explosions, the properties of and reactions involving nuclei far from stability play a key role. Models of core collapse supernova explosions provide an excellent example of the importance of this need for new nuclear physics information. These extraordinary events play a key role in nuclear astrophysics as they serve as the dramatic endpoint of the evolution of massive stars. Additionally, they most likely synthesize a large fraction of the heavier elements in the Universe via the r-process, and serve as a site for the γ- and p-processes as well. Exploring the possibility of r-process nucleosynthesis in supernovae requires advanced astrophysical models needing as input the properties of very neutron-rich nuclei and some neutron-induced reaction cross sections, most of which have never been measured. Cross sections of neutrinos with heavy nuclei, which are almost completely unexplored experimentally, also play an important role in supernovae. Additionally, electron capture rates on nuclei regulate the conditions during the explosion; they have to be known to understand the explosion mechanism and nucleosynthesis.

Studies of other stellar explosions also require advances in nuclear physics. Thermonuclear supernovae may be used as standard candles and therefore play a key role in understanding the evolution of the universe, but only if they are better understood. Their evolution, explosion mechanism, and nucleosynthesis depend on a better determination of electron capture rates on nuclei.

Observations of X-ray binaries with various observatories, possibly including future gravitational wave detectors, can reveal the nature of accretion processes and of the neutron star itself if the underlying nuclear reactions were better understood. Thermonuclear reactions during explosive hydrogen and helium burning at the neutron star surface during X-ray bursts involve mostly unmeasured reactions on unstable nuclei along the proton drip line - the rapid proton capture process (rp-process). Additionally, we need to understand electron captures and pyconuclear reactions in the crust of the neutron star, involving neutron rich nuclei out to the neutron dripline, which have never been studied.

Novae are thermonuclear explosions on the surface of accreting white dwarf stars, which are potentially important sources of certain light nuclei and gamma-ray emitters in our galaxy. Novae may also reveal details of the composition and evolution of white dwarfs. Currently, there are significant problems in our understanding of the explosion mechanism, nucleosynthesis and the connection between the nuclear event and the observed outburst. Observations will provide new insights if measurements are made of the proton capture reactions on unstable nuclides that occur during the explosion.

Our understanding of nuclear reactions and properties relevant for stellar explosions has made significant progress since the implementation of the last Long Range Plan. A number of first generation low energy radioactive beam facilities have been developed in the United States and Canada. All facilities have a dedicated astrophysics component on their scientific program. The Atlas facility at Argonne National Laboratory pioneered the use of long-lived radioactive species for nova and supernovae related measurements, Lawrence Berkeley National Laboratory has started a program of potential relevance for the evolution of super-massive stars, TWINSOL at the University of Notre Dame has centered its program on reactions in primordial Big Bang nucleosynthesis, and Texas A&M University is pioneering the establishment of the ANC method for a broad range of astrophysical applications. The HRIBF facility at Oak Ridge National Laboratory initiated a strong astrophysics program with post-accelerated radioactive ions presently focusing on the hot CNO cycles in novae. A fast radioactive beam facility has been designed with the coupled cyclotron project at the NSCL at Michigan State University offering unique opportunities for r- and rp-process measurements. At TRIUMF in Canada, ISAC will start operation soon as premier ISOL based facility, primarily dedicated to the astrophysics of explosive hydrogen and helium burning. These efforts, together with similar developments at European laboratories, demonstrated that radioactive beam experiments using ISOL and projectile fragmentation production techniques are both feasible and invaluable for nuclear astrophysics.

Great strides have been made in developing the experimental techniques needed for radioactive beam experiments. Direct reaction rate measurements with low-energy radioactive beams together with indirect measurements using higher-energy radioactive beams have given the first experimental basis to the rates of a number of important reactions in the rp-process. X-ray burst models have also benefited from half-life measurements of proton-rich nuclei up to Sn, which help constrain the location of the proton drip line. Significant contributions to our understanding of reaction rates of unstable nuclei in the rp-process came from transfer reactions and other indirect techniques at stable beam facilities. For r-process nuclei, first steps have been carried out at CERN to measure gross properties of a few r-process nuclei near the closed $N=50$ and $N=82$ neutron shells. These data have been very useful to constrain theoretical calculations of r-process input parameters. The experimental possibilities for comparable r-process nuclei studies in the United States are presently rather limited but the use of fragment facilities for producing r-process isotopes can be stimulated with the upgrade of the NSCL facilities. The experience with present facilities, however, also showed the limitations. The design specifications of the various facilities limit their applicability for a

broader range of experiments. Lack of beam intensity prohibits the measurement of low cross section reactions and reduces opportunities for extensive structure measurements near drip-lines. A vigorous and varied research program requires advancement in the state of the art that would accompany a new generation of radioactive-beam facility.
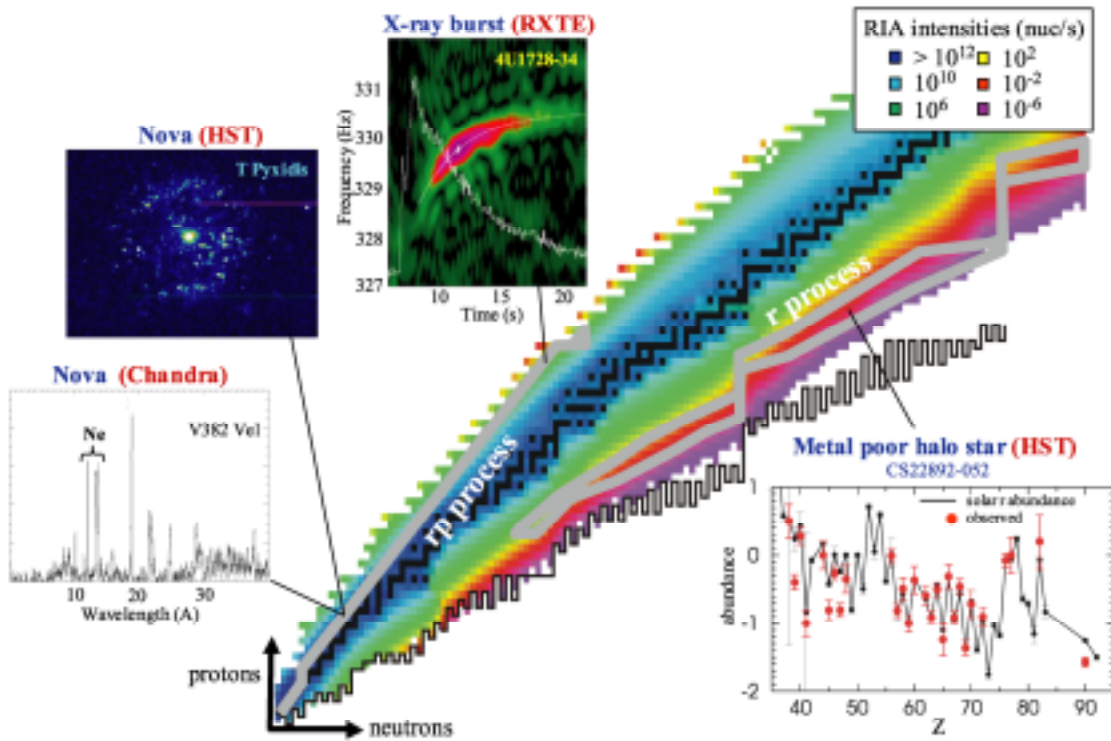

Figure 3: An N vs. Z chart highlighted by some of the areas relevant to a variety of explosive astrophysical scenarios, as measured in satellite observatories: rp-processing of light nuclei in nova explosions as observed in Hubble optical images and in Chandra x-ray spectra; on the surface of an accreting neutron star rotating with a period of 3 msec, an x-ray burst (with a 1 sec risetime) powered by the rp-processing of medium mass nuclei, as measured using the Rossi x-ray Timing Explorer; a remarkable comparison of the r-process abundance distributions for the solar system and for a very old, very metal poor star in the galactic halo, as determined by measuring its optical spectra with the HST.

To meet these challenges in nuclear astrophysics, a dramatic increase in the intensities of radioactive beams at low and high energies is essential. Only then can we use the latest experimental techniques to measure reactions with and the structure of unstable nuclei involved in stellar explosions. The Rare Isotope Accelerator is designed to meet this severe experimental challenge: it will provide unprecedented intensities of variable-energy, high-quality beams of proton- and neutron-rich radioactive nuclei. RIA will enable a significant fraction of all r-process nuclei to be studied, as well as the nuclei

along the neutron drip line that play a major role in processes taking place in the crust of a neutron star. Direct, low-energy reaction rate measurements on unstable proton-rich nuclei require the intensities that RIA will provide, as will measurements of the proton drip-line and indirect studies of proton capture rates up to the endpoint of the rp-process.

2.2.2   Nuclear physics in stellar evolution

The laboratory measurement of nuclear processes in stellar explosion desires the development of a new generation of radioactive beam facilities like RIA to simulate the conditions for rapid nuclear reaction processes within the split-second time-scale of a stellar explosion. Quite opposite conditions are necessary for the study of nuclear reactions during the long-lasting quiescent periods of stellar evolution. High intensity, low energy accelerators for stable beams are required to simulate within the human life span the thousands and millions of years lasting nuclear processes, which define the life time of a star. More than thirty years of intense experimental study have allowed us to define the major concepts of nuclear burning phases during stellar evolution. However, an increase in the precision of nuclear data is required in order to take advantage of the impressive advance in the quality of observational data. Furthermore, we recognize that the abundances of trace elements observed in grains and in stellar atmospheres contain a wealth of information about the stellar interior and the complex hydrodynamics that couple the interior with the surface (see Fig.4). Interpreting this information requires measurements of cross sections at the limit of sensitivity. New results will also lead to new observational tools and signatures. New measurements at the stellar energy range are needed for the understanding of the pp-chains, which control the energy generation in our sun. Improved reaction rates are essential for the final solution of the solar neutrino problem. Beyond that, questions of hydrogen burning in massive main-sequence stars through the CNO- and NeNa-, and MgAl-cycles still remain to be solved. Measurements of reaction rates at stellar energies would not only better define the hydrogen core burning conditions of massive stars but also the hydrogen shell burning conditions during the late phases of stellar evolution. The latter corresponds to higher temperature conditions and therefore may require the study of proton capture processes on isotopes up to Si and S at higher energies. These processes may influence the abundance distribution in planetary nebulae and can directly be correlated with the latest observational results. Of particular importance for the interpretation of energy-generation and nucleosynthesis during the red giant and asymptotic giant phase of stellar evolution is the measurement of α capture reactions down to stellar energies of ~300 keV. This does also involve the identification of α induced stellar neutron sources for the neutron-induced s-process, which is responsible for the origin of approximately half of the heavy elements in our universe. Beyond the accumulation of reliable data for nucleosynthesis, application of such data will create new observational tools and signatures. The detailed knowledge of reaction cross sections in the Gamow window coupled with observed abundance distribution in stellar atmospheres can be used for monitoring rapid convective and dredge-up processes in late evolutionary phases. It would offer a unique tool for simulating and testing the complex hydrodynamics in late stars and subsequently also in stellar explosion.
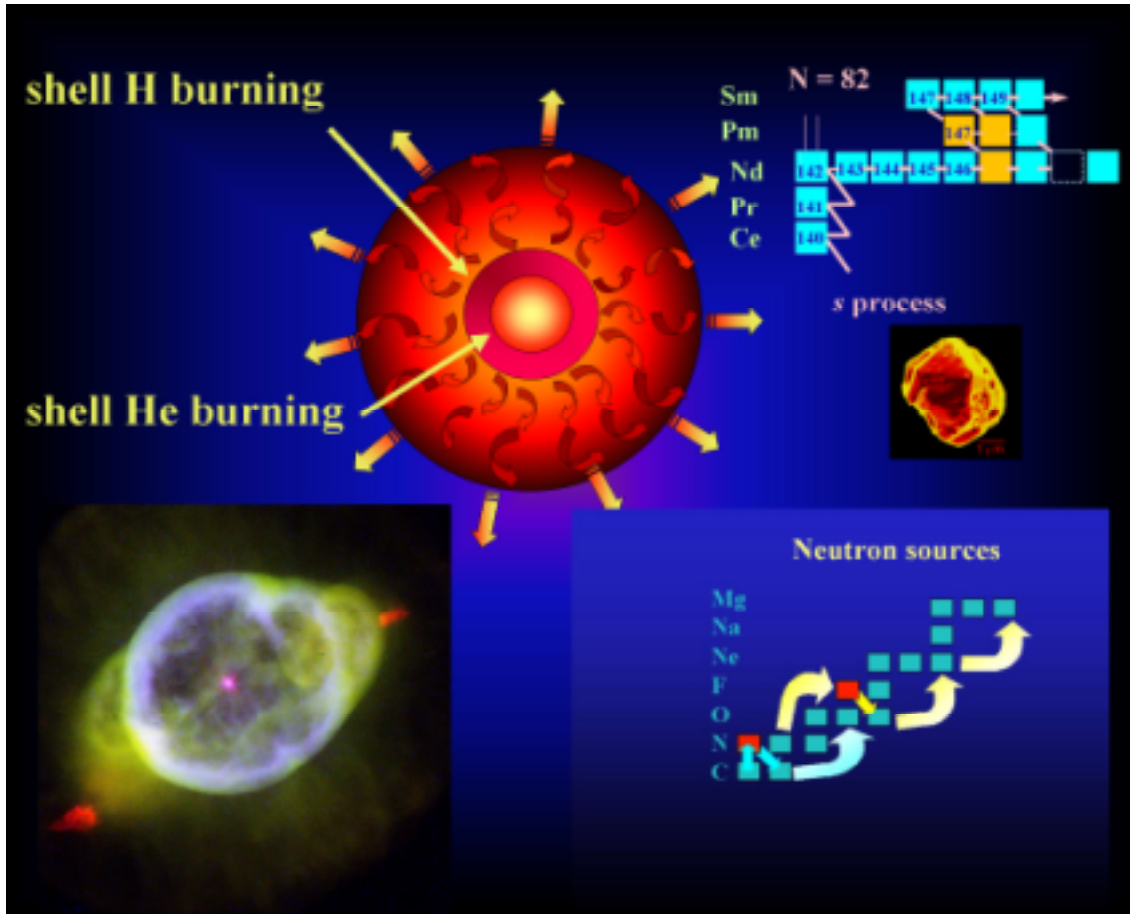
Figure 4: Nucleosynthesis processes during late stellar evolution e.g. AGB star. Freshly synthesized material from the hydrogen and helium induced reaction processes is dredged up to the surface of the AGB star (center) and ejected by radiation driven winds, forming planetary nebulae as observed by the HUBBLE telescope (bottom left). The material forms meteoritic condensates, the chemical analysis analysis of meteoritic inclusion (center-right) reveal nucleosynthesis signature. Convective mixing of hydrogen into the helium, carbon rich zone originates ^{13}C, in turn triggering ^{13}C(α,n) as main neutron source (bottom-right) for the s-process (top-right), which can form nuclei up to Pb, Bi by sequential neutron capture reactions.

Over the last few years the experimental efforts have focused on the use of small university based low energy accelerators at Notre Dame, TUNL, and Yale University to study the charged particle interaction processes that define the nucleosynthesis pattern during stellar evolution. These direct measurements of low energy nuclear reactions were often complemented by indirect measurements of the nuclear structure near the particle threshold, e.g. the ANC approach that represents the core of the nuclear astrophysics work at Texas A&M University. Neutron induced processes have been followed at facilities like ORELA at Oak Ridge and MLNSC at Los Alamos but the support in manpower and new developments clearly lag behind the situation at comparable European initiatives in s-process physics. New techniques are clearly necessary to improve the traditional approach in obtaining low energy data for charged particle reactions for stellar hydrogen and helium burning conditions. New developments would

permit the measurements of stellar reactions down to the actual stellar temperature range. Presently, the vast multitude of reaction rates for nuclear processes are based on extrapolation of high-energy laboratory data. These extrapolations can be off by many orders of magnitude depending on the nuclear structure and reaction conditions near the particle thresholds. Such deviations introduce substantial uncertainties in our interpretation of all the stellar processes that are centered on the basis of nuclear physics reaction rate data. This imposes limits on the validity of our solar model calculations through the uncertainties in the pp-chain reactions; it leaves open the interpretation of the CNO reactions for massive main sequence stars and its impact on later burning phases. It questions the basis of or description for the red giant and the asymptotic giant helium and carbon burning phase which are the sites for the s-process responsible for the origin of more than half of our known elements. It limits our interpretation and understanding of rapid convection processes that link the nucleosynthesis site deep inside the star with the stellar atmosphere where we can observe the freshly produced elements. To solidify our models, our interpretations, and predictions of stars and stellar processes we have to optimize the microscopic parameters for the nuclear engine of stars by minimizing the experimental uncertainties in the reaction rates.

New developments are presently being pursued at TUNL through the LENA project and at Notre Dame through JINA to overcome the fundamental experimental obstacles of extremely small cross sections and large cosmic ray induced background. New techniques for low count-rate measurements are being developed. This approach will help to push the measurements closer towards the Gamow range. At stellar energies, the background, however, exceeds the reaction-induced count-rate by many orders of magnitude. To address this problem a European initiative has formed to operate a first generation low energy accelerator facility LUNA at the European Gran Sasso Underground Laboratory to study nuclear reactions of importance for the pp-chains, which maintain the energy generation of our sun. The enormous reduction of cosmic ray background by two kilometers of rock shielding led to the first successful measurement of nuclear reaction at solar energy conditions. Further experiments in the next few years will help to address the remaining uncertainties in the reaction rates off the pp-chains and possibly also the CNO cycles.

While LUNA will serve as pilot facility for these measurements of solar reactions, a next generation underground accelerator would permit to extend these kind of studies also to stellar burning processes of massive stars in the hydrogen, helium and carbon burning phase. However, such a facility would require extensive R&D in the areas of accelerator design, gas-target techniques, detectors, and recoil separator development. Similar needs are associated with the RIA facility. However, the need for beam intensities in excess of 500 μA for achieving a rate of a few events per month will impose extremely stringent requirements on the experimental equipment and conditions, which may often exceed the requirements for radioactive beam experiments. An underground laboratory in the US might be the ideal site for such a facility and should be considered as a future development of the field.

2.2.3   Nuclear Astrophysics Theory

Nuclear astrophysics theory is concerned with modeling the macroscopic conditions for nuclear reaction and decay processes in stellar environments but it is also concerned with formulating and predicting the microscopic structure and reaction components that drive nuclear burning processes at the stellar conditions. Naturally, the latter aspect is closely related to and largely profits from nuclear reaction and structure theory.

Considerable progress has been made in astrophysical model calculations since the last Long Range Plan. The theoretical efforts in modeling a complete supernova explosion have not yet succeeded but important aspects of neutrino transport and interactions as trigger for revitalizing the supernova shock-front have been modeled. The neutrino-heated high-entropy bubble in supernovae has been established as the prime candidate for the site of the r-process. Strong observational evidence points towards the possibility of multiple r-process scenarios. Alternative or additional sites have been identified in merging neutron stars and the first model calculations for r-process nucleosynthesis have been performed. Two or three-dimensional modeling of stellar environments are crucial for a reliable description of convective and other mixing processes which were only approximated within the framework of traditional one-dimensional models. Convection and mixing has enormous impact on the abundance predictions for site-specific nucleosynthesis events. First steps have been made in two- and three-dimensional modeling of stellar evolution. This is of particular relevance for nucleosynthesis modeling in deep-convective AGB stars. First exploratory two- and three-dimensional calculations of novae, X-ray bursts, and supernovae have been performed. The results are beginning to shed light on the important rapid convection and mixing processes in stellar explosions. Complementary to these efforts is a better understanding of stellar hydrodynamics. Enormous efforts have also been made in improving the microscopic nuclear physics component. Large-scale network calculations have been made to simulate nucleosynthesis through stellar evolution to stellar explosion improved within the framework of one-dimensional models. The modeling of the s-process in AGB stars and during late stellar evolution of massive stars has been extremely successful. The network description of explosive hydrogen burning in Novae and X-ray bursts through the hot CNO cycles and the rp-process has been extended to provide a better understanding of the particular nuclear physics impact on astrophysical observables such as light curves and abundance distribution in the ejecta.

Nucleosynthesis in all stellar scenarios strongly depends on the quality of such reaction network simulations. Since most of the nuclear physics input data are based on global theoretical predictions a particular concern is the quality and therefore predicting power of nuclear structure and nuclear reaction models. Nuclear theories have been improved considerably to describe nuclei near and far from stability. This includes strong improvements in global models predicting masses, decay properties, and reaction rates, which provide the major source of nuclear structure input for the present rp- and r-process calculations. Structure calculations gave first indications of a quenching of the $N=82$ shell for very neutron rich nuclei leading to refinements in global mass models and strongly improved r-process predictions. Additionally, advances in the shell model

allowed for significantly improved calculations for proton- and electron-capture rates on unstable sd- and fp-shell nuclei.

A multitude of open questions and problems still remain and need to be addressed in the future. One major goal of future theoretical work must be to have more precise predictions for nuclear properties and nuclear reactions, particularly for nuclei located far from stability. This is of fundamental relevance for the computation of energy release and path of far off stability reaction sequences like the r- and the rp-process. Also for nuclei near stability, improved knowledge of the level structure near the particle thresholds is absolutely necessary for predicting low energy reaction components. Nuclear theory has made great progress in the ab-initio calculations of the properties of the very light nuclei (A<12) as well as in the phenomenological models for the properties of heavier nuclei. Many of the nuclear models are presently limited by computing power, and these will be improved by the use of new computing technologies. These include the Green's Function Monte Carlo and "no-core" configuration mixing calculations for the light nuclei and the large-basis shell-model calculations for heavy nuclei. Better predictions for nuclear masses can be based upon the microscopic mean-field model with corrections for nuclear correlations. The recently developed Hartree-Fock mass formula shows promise for a microscopic mass model. At present there is no unified nuclear model, but various models are needed to solve specific aspects of the nuclear many-body problem. For example, the features of light nuclei involving alpha-cluster configurations, which are important in the alpha-capture reactions, require models for which the clustering degrees of freedom are treated explicitly. The calculation of nuclear level densities requires a theoretical model, which emphasizes the statistical properties of the many-body configuration space. New ways must be developed to merge nuclear structure and nuclear reaction models, especially when the continuum spectrum becomes important near the drip lines.

Also in the realm of weak interaction processes substantial theoretical input is needed. Electron capture on iron group nuclei and neutron rich nuclei with Z<40 plays an important role in supernovae type Ia nucleosynthesis and in the early phases of type II supernova collapse where the capture deletonizes the core. The electron number of the core is crucial to the subsequent core bounce: the larger the trapped lepton fraction, the larger the homologous core and the stronger the resulting shock wave. Neutrinos produced during the collapse phase interact with other nuclei and with nuclear matter. The opacity of nuclear matter to neutrinos is one ingredient that drives supernova explosions. Neutrino induced processes also need to be better understood since they may have impact on the supernova shock front nucleosynthesis conditions.

All experimental and theoretical efforts must also include a vigorous, sustained program for the evaluation and dissemination of the nuclear data to astrophysics modelers. This program needs an active steering committee of astrophysicists to set its direction and to determine its priorities. This is essential to ensure the timely incorporation of experimental data in astrophysical model calculations. It will facilitate progress in theoretical astrophysics because well-documented, standardized nuclear physics input is a

prerequisite for comparing results from different research groups and allowing them to focus on astrophysical discrepancies.

3.   INFRASTRUCTURE AND RESOURCES IN NUCLEAR STRUCTURE AND NUCLEAR ASTROPHYSICS

The past success of low energy nuclear physics has profited largely from the available resources of experimental facilities and research opportunities at national and university based laboratories. The facilities and resources for large-scale experiments are mainly provided through the national laboratories. University groups have been and still are crucial not only in providing research personnel but also through providing the initial education and training for the next generation of nuclear scientists. The nuclear science research effort in the United States depends strongly upon maintaining this very effective balance that has developed between university and national laboratory research activities. Historically, this balance results from several unique aspects of the nuclear research endeavor centered on its needs for a diverse array of accelerator facilities to pursue its scientific and technical goals. This also includes the critical importance of the field for national security issues and energy production. Over the past decade new research areas have developed which present new opportunities and vistas for the future of our field. The upgrades of existing laboratories have broadened the range of experimental techniques, new instrumentation like GAMMASPHERE and recoil mass separators have been constructed, new demands arose from the broad range of application of nuclear physics in research, medicine, and industry. Nuclear physics is a thriving field; yet, there is reason for concern in the decline of funding for the university laboratories and in the rapid decline of nuclear physics representation in the university departments. This has severe consequences and threatens the very future of our field since these facilities continue to play a vital role in the recruitment, education, and training of the next generation of nuclear scientists. The education and training of graduate students is at the core of the education activities in nuclear science since it is these young scientists who will meet the demands for nuclear scientists for basic research and national needs.

The following section summarizes the present status of nuclear physics research and instrumentation at the national and university based laboratories funded through DOE and NSF grants. It also gives a short summary about the anticipated research plans and efforts for the future. Special attention will be given to the present status of graduate student education in the US and the possible impact on the future of the US nuclear physics program. For details we refer to a more detailed study that has recently been performed for the long-range plan. The results have been summarized in a white paper "On Future Concepts and Perspectives for University-Based Research and Graduate Education" (http://nucth.physics.wisc.edu/dnp/town/education.pdf).

3.1   National Laboratory and University Accelerator Facilities

Nuclear Structure and Nuclear Astrophysics research is mainly carried out at university and national laboratory based accelerator facilities. Thus the continuous modernization of the facilities and instrumentation is necessary to maintain a successful and competitive research program. While each of the facilities has notable strengths, the different research

programs carried out at the various accelerators complement one another in many important ways. Together they are part of a coherent national effort in low energy nuclear science. While the long-term progress of the field requires the design and development of the next generation radioactive beam facility RIA, the wide range of scientific questions and problems in nuclear structure and astrophysics requires the maintenance of the present accelerator facilities at a competitive level. In addition to being the backbone of the current programs the existing accelerators will play a crucial role in carrying out critical R&D relevant to RIA as well as in ensuring the existence of a healthy community of researchers and students when RIA comes online.

3.1.1 National Laboratory Based Facilities

The Argonne Tandem-Linac Accelerator System (ATLAS) at Argonne National Laboratory has a broad-based program in low energy nuclear science. The ATLAS facility provides a large international community of users high quality beams of stable isotopes from protons to uranium as well as a variety of radioactive beams. The laboratory has played a vital role in the exploration of radioactive beam techniques with the development of off-line produced radioactive beams. This initiated a strong nuclear astrophysics program at the laboratory. The construction of the FMA recoil mass separator set new standards in use and versatility. The use of the FMA was instrumental for a pioneering study of proton emitters to map the drip-line. These experiments employed successfully a broad range of Si-strip detector arrays. The FMA was also instrumental in conjunction with GAMMASPHERE for the successful application of recoil tagging techniques for nuclear spectroscopy up to the very heavy nuclei. 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 for ISOL-type beams of exotic isotopes at RIA. 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 the future RIA project. Scientists and engineers from several divisions at Argonne are actively pursuing the development of the technologies that form the underpinnings of RIA. 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 RIA.

The Holifield Radioactive Ion Beam Facility (HRIBF) is a first-generation ISOL radioactive ion beam (RIB) facility developed in a cost-effective way to make use of existing accelerators at ORNL. Radioactive species are produced by intense light-ion beams from the Oak Ridge Isochronous Cyclotron (ORIC) and post-accelerated by the 25MV tandem electrostatic accelerator. Linking production and post-acceleration is the RIB Injector system consisting of a high-voltage platform on which the production target ion source resides and beam preparation and purification hardware. The suite of radioactive beams available for research is expanding rapidly. Several high-profile experiments with neutron deficient beams in nuclear astrophysics and reaction physics have been completed in the past year. Currently, HRIBF is the only facility in the world

capable of providing accelerated beams of medium mass neutron-rich RIBs. This capability of the HRIBF will remain unique in the world for the next several years. The HRIBF has made significant contributions to the technology of RIB production, including new-concept ion sources optimized for RIBs, and novel, highly effective production-target formats. A great strength of the facility is the suite of state-of-the-art experimental equipment, carefully optimized for nuclear structure and nuclear astrophysics research with RIBs, including two recoil separators, a gas-filled magnetic spectrograph, the CLARION gamma-ray array, the HYBALL charged particle detector array, and several highly-segmented Si-strip arrays, specialized detectors and electronics for decay studies, and detectors to monitor and help tune low-intensity RIBs. Many of the existing and planned experimental tools and equipment have direct application for future research at RIA. Similarly, the HRIBF can continue to play a key role in the training of manpower and development of ISOL radioactive beam research while RIA is being developed and brought on line. The performance and efficiency of this facility can be dramatically enhanced with a modest investment of new funds in the interim period.

The 88-Inch Cyclotron at Lawrence Berkeley National Laboratory supports a wide range of low energy nuclear science for a large international community of users. The central component is a sector-focused, variable-energy cyclotron that can be fed by either of two ECR ion sources. This versatile combination produces heavy-ion beams of elements throughout the periodic table. For helium to oxygen, beam energies are up to 32 MeV/nucleon; for heavier ions the maximum energy per nucleon decreases with increasing mass reaching 5 MeV/u at bismuth. Light ions are available at intensities of 20 pμA. The unique combination of high intensity stable beams such as ^{51}V, ^{64}Ni and ^{86}Kr and the BGS high efficiency separator are essential for the production and detection of new superheavy elements. GAMMASPHERE, the world's most powerful instrument for detecting gamma rays, is currently in full operation at the 88" Cyclotron and serves a large, active users community for a broad range of physics studies including nuclear structure studies and fundamental symmetry. The BEARS project has recently delivered with ^{11}C its first accelerated radioactive beam on target. Berkeley scientists have made important contributions to the present generation of instrumentation for research in this area, including advanced ECR ion sources, GAMMASPHERE, the BGS, and the Facility for Exotic Atom Trapping. VENUS, a next generation ECR ion source, construction at Berkeley will not only greatly extend the scientific reach of the present 88" Cyclotron-based research program, but may be the source of choice for the high intensity heavy ion driver linac of RIA. Effective pursuit of new physics opportunities at this facility would greatly benefit from improved funding.

There are two neutron beam facilities in the US that have traditionally carried out extensive programs in nuclear astrophysics with neutron beams, ORELA at Oak Ridge National Laboratory and MLNSC at Los Alamos National Laboratory. Their efforts are based on the use of a high intensity pulsed white neutron beam with time-of-flight analysis. The neutron flux is created at ORELA by a ~50 MeV electron beam through (γ,n) reactions on heavy target material and at MLNSC by high-energy proton beam spallation processes. The operation of MLNSC is mainly supported through funds of the defense and basic energy science programs of DOE, but the nuclear astrophysics program

appears to be an essential component for new developments. Presently, the facility is operated under a Memorandum of Understanding between the various offices of the DOE wherein the Office of Science has agreed to keep ORELA operational for the Nuclear Criticality Safety Program. Nuclear astrophysics research has continued, but lack of funding and manpower, as well as deferred maintenance jeopardizes the long-term future of this once premier facility. A modest amount of funding would prevent the permanent loss of this unique facility and the related expertise. This would also keep open the possibility of exciting opportunities in nuclear astrophysics at the future high flux Oak Ridge Spallation Neutron Source, SNS.

3.1.2   National Superconducting Cyclotron Laboratory

Based on the exciting scientific opportunities with rare isotope beams the highest priority for new construction in the last long-range plan included the upgrade of the National Superconducting Cyclotron Laboratory. The upgrade of the NSCL to the coupled cyclotron facility (CCF) is nearing completion and funds to enable an efficient, reliable, and user-friendly operation of this new radioactive beam facility are necessary to realize the scientific potential. The construction and operation of this facility is extremely important for the advancement of nuclear structure and nuclear astrophysics during the next decade before RIA is available since the CCF will represent the premier facility for in-flight radioactive beam physics in the North America in the next future.

Compared to what was possible with the stand-alone K1200 cyclotron, the CCF will provide large intensity gains of intermediate-energy primary beams, from light ions up to uranium. For very heavy ions (A >150), the CCF will also provide a significant increase in energy. Together with the increased acceptance of the new A1900 fragment separator, intensity gains by factors of 100 – 10,000 will be achieved for most fast beams of rare isotopes. These beams will be 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. Experiments at the NSCL will identify the key scientific issues for the next generation of rare isotope.

The upgraded NSCL will lay the groundwork on which a significant part of the scientific program at RIA will be built. The NSCL must and will also play a major role in the R&D effort for RIA. For example large area neutron and charged particle detector arrays developed at the NSCL can be used at RIA. NSCL will continue to play a major role in training of the next generation of nuclear and accelerator scientists.

3.1.3   Low Energy University Based Facilities

As the primary locations for attracting and educating the undergraduate, graduate and post-graduate students who will constitute the next generation of nuclear scientists, university based programs, including NSCL, are crucial for the future of nuclear science.

Many of the university based accelerator facilities maintain an independent active research program complementing and feeding the research efforts of the national facilities. In order to assure that these laboratories can continue to fulfill their scientific and educational missions, the university facilities need to be operated on an up-to-date technological level. To remain competitive on the national and international level often substantial increases in funding are required.

The low to medium energy federally supported university accelerator facilities at Florida State University, Notre Dame, Stony Brook, Texas A&M, TUNL, Yale and the University of Washington are a very productive component of the national program. The accelerators at these facilities deliver a wide variety of light to heavy ion beams ranging in energy from a few MeV/u up to 80 MeV/u. An important and diverse component of detectors, high performance spectrometers and special purpose beamlines, specifically designed to match the accelerator capabilities are in place. Essential and innovative research in nuclear structure, nuclear astrophysics, nuclear dynamics, fundamental interactions, and in applications of nuclear techniques is carried out at the university facilities. Significant radioactive beam capabilities have been developed at Notre Dame and Texas A&M. New efforts for pursuing low energy studies of astrophysical interests have been initiated at Notre Dame and TUNL. The use of polarized beams for astrophysics related experiments represents a fascinating new development. Complementary techniques and ideas for nuclear astrophysics experiments have been developed and are being pursued at Texas A&M, TUNL, Yale and the University of Washington. Strong research programs in nuclear structure are pursued at Florida State University, Notre Dame, Texas A&M, TUNL, and Yale using a broad and complementary variety of nuclear instrumentation. In particular, the nuclear structure program at Yale focuses on collective modes and structure evolution in nuclei with an entirely new suite of state-of-the-art instruments. Forefront research on the international level in fundamental interactions has been performed at Stony Brook and is also being pursued at Notre Dame. In addition all these facilities provide the basis and substantial technical infrastructure for user programs at larger national and international facilities.

The university programs are extremely cost-effective. Operating funds of these university laboratories are relatively modest and federal investments are matched by very significant investments by the universities. Nevertheless, in recent years, the relatively flat funding of nuclear science and the ever-increasing expense of operating the large national facilities has put a disproportionate pressure on funding for the University laboratories. The increases needed in both operating and instrumentation funding for the next five years are absolutely essential for maintaining the vitality of the field. There are very general needs for state of the art detectors, new electronics and modernization of major equipment. There are also specific upgrade plans for Texas A&M implementing additional radioactive beam capabilities and TUNL pursuing a nuclear physics and nuclear astrophysics program at the Free Electron Laser Laboratory (1.2-GeV DFELL). We recommend that appropriate increases of funding for the university facilities be made to assure the continued effectiveness of the research and training programs at these facilities during the period of this plan.

3.2　　　　Future Facilities and Instrumentation

Presently a very active research program is carried on at the existing facilities making extensive use of the recent upgrades and developments. A broad range of programs in nuclear structure and nuclear astrophysics has been established around the existing radioactive beam facilities in the US and Canada and these will continue throughout the time frame of the long range plan. With the completion of RIA construction, an unprecedented number of new opportunities in nuclear structure and astrophysics will become available.

The research with rare ion beams within the next decade will concentrate on the use of ATLAS (ANL), HRIBF (ORNL), and the NSCL (MSU) for both, nuclear structure and nuclear astrophysics experiments. The BEARS facility at LBNL may also serve as a test ground for future radioactive beam experiments. Collaborative efforts with Canada's new ISAC radioactive beam facility will focus on nuclear astrophysics questions in particular. Because of the anticipated high beam intensities, studies at ISAC will be of extreme relevance for developing experimental techniques for nuclear astrophysics experiments at the future RIA facility. On the other hand the coupled cyclotron (CCF) at the NSCL will most likely be the dominating facility to pursue the development of fragment beam techniques for RIA. Large collaborations have been formed to coordinate the broad range of experimental and technological tasks ahead.

Major activities are also anticipated for the future of stable beam experiments. The nuclear structure community centers its goal on the development of new generations of gamma and particle detector arrays to probe the nucleus at the limits of angular momentum and deformation. These studies will focus on the development of gamma tracking techniques within the next decade using the presently available national laboratory and university accelerator facilities.

The nuclear astrophysics community on the other hand sees its goals in the study of reactions at very low energies to probe the nucleus near the particle thresholds, which corresponds to the range of stellar excitation. This approach is guided by a large range of indirect studies utilizing transfer measurements (ANC method) as well as photo-excitation and dissociation techniques with virtual (Coulomb-dissociation) and real photons (DFELL). These studies may open new windows for probing nuclear astrophysics reactions complementing the present attempts for direct measurements towards lower energies. In the long range we identify the need for a direct measurement of the key reactions of stellar evolution and nucleosynthesis at stellar energies, which will require a completely new concept of low energy reaction studies.

In the following we summarize the three major technical goals and developments we anticipate necessary for the successful future of nuclear structure and nuclear astrophysics.

3.2.1 The Rare Isotope Accelerator (RIA)

RIA is the highest priority for new construction for the fields of nuclear astrophysics and nuclear structure and dynamics. The basic RIA concept was developed by the NSAC ISOL Task Force (Grunder Committee) and has been discussed in the final report of that committee (http://srfsrv.jlab.org/ISOL/). The present RIA concept is an evolution of the Advanced ISOL Facility that was endorsed by the last Long Range Plan, together with the NSCL upgrade, as the highest priority for new construction. The realization of RIA depends on the immediate availability of funds to support significant R&D on accelerator technology and experimental equipment. Special attention has to be given to the needs and requirements for detectors and other experimental equipment necessary for the successful establishment of a fully operational scientific program at RIA. These needs have been formulated in a series of RIA related workshops and town meetings and are summarized in the white papers on "Experimental Equipment for an Advanced ISOL Facility" (http://www.nscl.msu.edu/conferences/riaws00/isol_exp_equipment.pdf) and "Scientific Opportunities with Fast Fragmentation Beams from the Rare Isotope Accelerator" (http://www.nscl.msu.edu/research/ria/whitepaper.pdf).

3.2.2 Gamma-Ray Energy Tracking Array

The 1996 long-range plan recommended the development of a new generation of gamma-ray detector arrays (such as GRETA, http://greta.lbl.gov/lrp.html) based on the concept of gamma-ray tracking. The feasibility of gamma-ray tracking has now been successfully demonstrated with prototypes. It is important that we capitalize on this success by continuing to support such detector development and subsequent construction. A gamma-ray tracking array is the only detector which can satisfy the requirements of experiments using low energy stable beams, low energy radioactive beams produced by the ISOL method, and high-energy radioactive beams from fragmentation. The details of the geometry will be determined by the requirements of the physics questions to be addressed. The importance of gamma-ray tracking to a broad range of physics research may justify development and implementation of more than one array, and the implementation must be pursued without delay to maintain the leadership role of the US in the field.

3.2.3 National Underground Accelerator Laboratory

A US underground laboratory has been identified as the most important goal for the neutrino community. A committee has been formed to identify the scientific potential and to discuss possible sites for the laboratory and for the next generation of underground neutrino detectors (http://apollo.sns.ias.edu/~jnb/). This of course also introduces new opportunities for the low energy nuclear astrophysics community to follow the European example of LUNA at the Gran Sasso underground laboratory in developing an underground accelerator facility to study nuclear reactions at stellar energies in a cosmic ray free environment. However, considerable improvement is necessary in technique and

design to overcome the problems of beam induced background. A high intensity low energy (~1 MeV/amu) heavy ion accelerator in ac-mode will provide better conditions than the LUNA light ion machine. Inverse kinematics techniques provide higher efficiencies and event identification through timing and particle identification with a next generation recoil separator system with beam rejection power of better than 10^{-20} of the total system. Such a facility requires extensive studies on the accelerator aspects, gas-target techniques, and recoil separator improvements. These studies are in close correspondence to and will profit from similar developments for the RIA facility. However, the need for beam intensities of up to 1~mA for achieving a rate of a few events per month will define extremely stringent requirements for the experimental equipment and conditions which may often exceed the requirements for radioactive beam experiments. Therefore extensive R&D studies are necessary to investigate the feasibility of such a project.

3.3   Manpower and Training

As discussed in the previous sections the field of low energy nuclear physics is thriving, both in its goals towards the understanding of the nucleus itself and as astrophysical engine for stellar processes and for the origin of the elements. New experimental techniques have been developed and implemented, NSCL has been upgraded to operate as one of the world premiers fragment separator facility, RIA is being considered as the main new construction object for the next long range plan period to answer the broad range of open scientific questions. A wide variety of industrial and medical applications have been pioneered over the last decades and have converted low energy nuclear physics techniques to a tool of domineering impact for all aspects of our society. However, the field is haunted by the concern about the future generation of nuclear scientists necessary to continue the present efforts not only in research but also in the broad range of applications necessary for the national needs of our society. These concerns have already been addressed for the entire nuclear physics community in a white paper on educational aspects for the long-range plan (http://nucth.physics.wisc.edu/dnp/town/education.pdf). In the following we will concentrate of the specific manpower situation, problems, and needs in the fields of nuclear structure and astrophysics. We will try to evaluate the present situation and its consequences on the future of the field.

Over the last two decades the field of nuclear structure and astrophysics has witnessed a fundamental change in the infrastructure and sociology of research and research groups. Smaller university based research facilities have disappeared while research and funding efforts have focused more and more on larger user facilities. This development may be explained by the significant trend toward increasing size and complexity of experiments and of accelerators requiring increased operational funding investments in a time of relatively static budgets. This has led directly to an increasing centralization at national facilities and a serious constraint on financial support for, and a decrease in university based facilities and centers. While this seems to be a general tendency in nuclear physics, its belated development has significant consequences for the present status and future of low energy nuclear physics at universities and will have severe consequences also on the

future operation of the larger national laboratory facilities. In view of the manpower intensive long-range interests of the field, the present situation needs to be recognized and remedied.

The decline of funding for university laboratories has largely prevented a modernization of the facilities and the associated equipment despite continuous research activities. Consequently low energy nuclear physics is sometimes viewed as outdated and unfashionable by department heads and students. Since research should not be judged by fashion standards but by its needs for science and society, this notion causes regrettable psychological difficulties for student and faculty recruitment efforts. This development is underlined in the demographics of graduate student enrollment in nuclear structure and astrophysics, which continues to decline. This development not only threatens the continuation of research and development in the field at universities and national laboratories but it may also have severe consequences for the man-power situation in associated non-academic areas. The demand of students with degrees in low-energy nuclear science is high in industry and other fields of employment. In particular the broad range of medical applications of nuclear physics techniques requires continuous education in accelerator and detector technologies. The manpower for defense and energy research traditionally has been recruited from this community. Stockpile stewardship may be in jeopardy.

While the consequences for the larger society are manifold, we will concentrate in the following on the consequences for low energy nuclear science research and the role of universities for this national enterprise. Traditionally the universities have two primary responsibilities:

- Carry out forefront research in fundamental aspects of nuclear science,
- Attract and educate the next generation of nuclear scientists for both fundamental research and to meet the national need for scientists in applied nuclear science.

That the universities have met these responsibilities is evident in the current strength of the existing national research program. University groups are involved in all aspects of the program. These groups constitute the major portion of users at national facilities and they also pursue and carry out exciting research in all aspects of nuclear science employing the full diversity of facilities available. By any measure, university groups have been very successful in these activities but the decline in student enrollment and the changing nature of the field threatens the continued vitality of these programs.

The decrease in the number of competitive university facilities threatens the national research activity. The university facilities occupy a very substantial niche in the national program, complementary to the research facilities at the national laboratories. They carry out interesting and important research in structure, nuclear astrophysics, fundamental interactions, nuclear reactions and nuclear applications. They have made, and continue to make, important discoveries and develop parallel important new techniques for advancing the field. In addition to greatly increasing the breadth and diversity of the program, the university facilities also provide critical additional technical support

infrastructure for the field. Many of the instruments employed in the national facilities have been designed and constructed at the universities. University based research is also extraordinarily cost effective. Approximately one half of the scientists working in nuclear science are in the universities. Including personnel salaries the total university contributions to the nuclear science program are essentially equivalent to the funds granted to universities by NSF and DOE.

In this role the universities provide the critical education and training of the young scientists- undergraduate, graduate and post-doctoral, who will meet the demands for nuclear scientists for basic and applied research. It is at the universities that future nuclear scientists are identified, educated in the basics of our field, and mentored in their education and training. It is also at universities that young nuclear scientists are exposed to formal studies and the intellectual excitement of physics and chemistry, in general. This broad exposure to areas of science other than nuclear science is critical in educating and training future scientists to meet the needs of the full spectrum of national activities in applied nuclear science.

The university facilities and centers serve as vital attractors for students, both graduate and undergraduate to meet the national manpower needs. Traditionally, the university-based nuclear laboratories have been particularly important to the training of graduate students in the techniques and science of our field. The greater flexibility of use of these facilities makes them ideal to provide hands-on student training not easily obtained at the national facilities. At university laboratories the graduate students are exposed to and participate in the complete spectrum of activities in experimental science. They typically play an active role in the design construction, calibration, and/or maintenance of apparatus, in addition to exploiting these instruments for research. In addition they are actively involved in the data taking, analysis, and interpretation of their results. Given the smaller scale of projects at university labs, and the less restrictive time constraints, the students can develop into true experimentalists with a breadth of technical skills, poised to become leaders in the field. These facilities, although shrinking in number, will continue to play a vital role in the education of the next generation of nuclear scientists. *Given the importance of the forefront research conducted at university laboratories, as well as the unique role they play in educating and training young nuclear scientists, strong support of university based research groups and facilities is critical to the continued health of nuclear science research and education in the United States.*

Over the next decade, with the advent of more powerful exotic beam facilities, culminating in RIA, there will be need for a large, active, engaged community of scientists and students for research and for instrument development, as well as engineers and technicians to realize specific instruments. The construction of RIA as the new major initiative in low energy nuclear physics would be the driving stimulant for strengthening and rejuvenating existing programs at present national laboratories and universities. It would motivate the creation of new faculty positions, which in turn would attract new generations of students to this exciting field. This is witnessed by the impact of the present radioactive beam initiatives to the manpower situation in the field. The recent Megascience Forum report estimates a worldwide community of researchers and students interested in exotic nuclei at about 2000, with about 600 each in the US, Europe, and

Japan/China. This provides a large talent pool that will further attract new researchers when RIA approaches reality, just as has happened in the last decade with the construction of other major new nuclear physics facilities. While RIA represents the scientific future of the nuclear structure and nuclear astrophysics community, the continued cultivation of the scientific manpower pool in the interim prior to RIA operation entails the continued operation of existing low-energy nuclear physics facilities.

4.   APPLICATIONS OF NUCLEAR PHYSICS TECHNIQUES

A wide variety of industrial and medical applications have converted nuclear physics techniques to a tool of domineering impact for all aspects of our society. The premier tools and techniques in nuclear physics have been developed over the last twenty years of basic research in low energy nuclear physics. There is an immense range of applications that have emerged from this enterprise entertaining beyond the traditionally known aspects of energy and defense all branches of human enterprise in medicine, engineering, science, geo-science, arts, and history. Application and interdisciplinary research not only provide an array of important benefits to mankind but they involve a rapidly growing workforce that needs to be kept educated in the rapidly increasing number of possibilities but also complexities of the applied techniques. Anthropology, archaeology, and the arts not only employ the classical ^{14}C dating method but also develop increasing sensitivities with accelerator based mass spectrometry. Medical applications involve a broad range of radiation therapy techniques, PET and MRI diagnostic imaging, radioisotope production for medical treatment, diagnostics, and biomedical research. Materials research employ tracer ion implantation, single event upset, neutron scattering, neutron/proton radiography, PIXE/PIGE, μSR/μ-NMR, and a host of other diagnostic techniques. Safety and security concerns utilize nuclear physics detection systems and sensitivities as well as forensics and criminology. This wide spread of applications has already been addressed in previous NSAC long range plans. Specifically mentioned are the range of nuclear physics techniques for art analysis and archaeological dating in the LRP of 1983 and 1989. The rapid employment for medical diagnostics and treatment has been addressed in the LRP of 1989 and 1995, with the latter also addressing the large number of additional applications for environmental science, material science, energy production and national safety and security issues.

We therefore want to concentrate in this white paper on specific application techniques and interdisclipinary research opportunities with rare ion beams as supplied by a future RIA facility. The possibilities center on four separate application areas:
- radioisotope production and biomedical research;
- nuclear physics needs for science-based stockpile stewardship;
- R&D related to accelerator transmutation of waste;
- materials science and other applications.

These topics and opportunities have been addressed in a recent workshop at Los Alamos National Laboratory on applications of rare ion beams at RIA. The main conclusion was that applications and interdisciplinary research are an important aspect of ongoing nuclear science activities that should be implemented in the planning and design of a RIA facility. The workshop summary and proceedings can be found at the following web site http://www.lanl.gov/orgs/t/workshop/homepage.htm. In the following we present the conclusions of the applications working group in terms of the four RIA-related applications areas mentioned above. We include a discussion of facility implications for applied/interdisciplinary research at RIA, and a short section highlighting current applications.

4.1   Radioisotope Production and Biomedical Research

With RIA's very high beam intensity and its mass and fragment separation capabilities, there is a significant opportunity to produce a wide variety of radioisotopes of interest to the biomedical research community and others. It is possible to peel off a small portion of the primary beam at the first stripper and use (HI,xn) reactions to produce a variety of neutron-deficient isotopes in high purities which are not currently available, such as the alpha emitter ^{149}Tb produced via the ^{141}Pr(^{12}C,4n) reaction. The ability to collect extraordinarily high specific activities of long-lived species using the fragment separator and/or the mass separator should be implemented in the general design plan of the facility. In particular, at a separated radioactive beam intensity of 10^{11}/s, this corresponds to a collection rate of ~10^{16} atoms/day or ~3 µg/day at A=200. The availability of such high-purity (mass-separated) radioisotopes will greatly advance future research in the development of radiomedical diagnostics and radiotherapy. The ability to post-accelerate radioactive species and implant them into various substrates (such as seeds and stints) is also well suited to evolving radiotherapy applications.

4.2   Physics Needs for Science-Based Stockpile Stewardship (SBSS)

SBSS is aimed at certifying and maintaining the nation's aging nuclear stockpile. Achieving this goal in part involves obtaining an improved understanding of the nuclear physics, where much of the uncertainty lies in our knowledge of nuclear reactions off the line of stability. RIA will provide the capability to measure important reaction cross sections and to test and ultimately improve models that calculate them. The use of inverse kinematic reactions using radioactive beams, such as ^{8}Li(p,t) and ^{239}U(d,pf) to simulate (n,f) reactions, represent a powerful tool for measuring these cross sections. For long-lived species ($t_{1/2}$ > 2 d), it is possible to collect pure mass-separated samples in target quantities that then could be taken to a high-intensity neutron facility for the measurement of neutron-induced reactions, such as (n,γ), (n,xn), or (n,f). These and selected reactions involving nuclear isomers are extremely important measurements for the SBSS program. Finally, interest was expressed in the onsite production of neutrons at RIA using either the primary beam or from a separate neutron generator co-located at RIA to carry out neutron-induced reaction measurements on short-lived radionuclides and isomeric species. This program actually might complement similar experimental efforts for studying astrophysics motivated neutron induced processes.

4.3   R&D for Accelerator Transmutation of Waste (ATW)

ATW technology aims to transmute, through fast (10 keV-20 MeV) neutron-induced fission and radiative capture reactions, long-lived radioactive species into shorter-lived species with half-lives typically less than 300 years. RIA could be used to collect pure mass-separated samples of selected actinide and fission product species and produce radioactive targets for the measurement of the important fission and capture cross

sections at a neutron facility. Fission probabilities could also be measured in inverse kinematics (d,pf) or similar stripping reactions, which mimic (n,f) reactions (at least at neutron equivalent energies above ~0.5 MeV). Other studies, such as those recently performed at GSI, involving the measurement of spallation and fission product distributions following A+p inverse kinematic reactions have been instrumental in testing and improving intranuclear cascade and pre-equilibrium models used in ATW calculations. Additional measurements of this type would be extremely valuable in further improving these models.

4.4   Materials Science and Other Applications

The use of radioactive tracers implanted into materials is a developing and potentially powerful tool for the field of materials science and surface physics. In particular, radioactive beam implantation is important for wear and corrosion studies, beta-NMR studies of high T_c superconductors, semiconductors, magnetism, and perturbed angular correlation studies of materials are important potential applications. At RIA intensities, material modification studies using doping and annealing techniques could also be done. Other areas of interest include space radiation effect studies with stable and radioactive beams, radioactive beam implantation for medical radiotherapy (see the biomedical applications section), neutron cross sections, neutron damage, and radiation effect studies with high-energy (20-400 MeV) neutrons produced by projectile fragmentation. The possibility of slowing these neutrons down to ultra-cold temperatures may provide also an alternative production site for ultra-cold neutrons. At present, the commercial use of radioactive beams appears to be a limited, but viable option.

4.5   Facility Implications for Applied Research at RIA

Although some of the applied research discussed here would utilize the primary post-accelerated, high-intensity RIA beam, many experiments could be run as a secondary (or parasitic) user. In particular, flexibility should be built into RIA to utilize multiple targets, beam switching/sharing, and broad-range mass separation or pre-separation/post-separation fragment separator ideas to feed multiple users. Although the community is concerned about facility creep, many of these ideas are relatively simple and cost efficient if implemented up front. If sufficient room and flexibility is designed into the target and initial mass separation/recoil selection regions, other more involved ideas could be implemented as future add-ons. Increasing beam usage and flexibility is the key.

To foster the application components and opportunities at RIA the design should include the capability to collect mass-separated/recoil-separated radioactive samples for the production of long-lived ($t_{1/2} > 2d$) radioactive targets. It should also provide the opportunity for building a high-intensity area to utilize the stable heavy ion beam from the driver accelerator to make radioisotope production via (HI,xn) reactions. Additional RF power maybe required in the early stable beam acceleration stages to fully utilize this latter capability.

The production and use of neutrons at RIA also presents interesting opportunities. Projectile fragmentation will provide a relatively intense source of high-energy neutrons focused at forward angles. By pre-bunching the beam at ~1 MHz, neutron time-of-flight experiments may be undertaken. Moreover, the directional nature of these projectile neutrons maybe efficiently utilized for the production of ultra-cold neutrons using a special moderator located close to the target after a sweeping magnet. RIA with its high-intensity, light ion beams would also provide an excellent source of spallation neutrons. Although not wanting to compete with other spallation sources, the spallation neutrons produced at RIA could be very useful for neutron-induced reactions on the short-lived rare isotopes and isomers produced and collected at RIA. Finally, the possibility of a small stand-alone neutron generator system, such as a d+d accelerator, was explored as an alternate low-energy, tunable (from 2-20 MeV) neutron source. Although a high degree of interest was expressed related to neutrons at RIA, further study is required to develop the best option(s).

Through our innovative scientists and facilities, the nuclear science community plays an important role in advancing nuclear-related interdisciplinary research and applications whose benefit to our society should not be overlooked. We should remain diligent in fostering and further advancing such work at our current facilities and we should be forward looking to include these activities when planning future facilities such as RIA. In particular, the high-intensity heavy ion beams that would be available at RIA represents a new paradigm for radioisotope production and the ability to collect mass and recoil separated radioactive species has important ramifications to nuclear medicine and national security.

5.   INTERNATIONAL ASPECTS

The nuclear structure and nuclear astrophysics community carries out a very intense forefront research program at a broad range of national laboratory and university based accelerator facilities. Similar programs carried out worldwide by the international community of nuclear scientist mirror these efforts. These international programs compete and complement the US research efforts; their existence underlines the continuous broad interest in these aspects of low energy nuclear physics. Over the last decades the research communication has remained vital through strong transatlantic and transpacific exchange of ideas or even collaborations. This has created a close community with strong common interests and goals.

The research efforts in nuclear structure physics outside the US are based on a broad range of small and medium scale accelerator facilities complemented by reactor laboratories. This includes CRC at Louvain-la-Neuve (Belgium), JYFL in Jyväskylä (Finland), GANIL at Caen (France), the ILL high flux reactor in Grenoble (France), IreS at Strasbourg (France), GSI in Darmstadt (Germany), INFN, LNL at Legnaro (Italy), RIKEN in Tokyo (Japan), DUBNA (Russia), CERN-ISOLDE (Switzerland) and several smaller university based accelerator facilities worldwide.

5.1   Radioactive Beam Facilities

There is a strong trend in the international nuclear structure community towards measurements far off stability in particular with the use of rare ion beams. This trend has initiated the development and construction of a whole series of small to medium scale radioactive ion beam facilities worldwide. These facilities utilize both in-beam fragmentation based separation techniques as well as ISOL based techniques for the beam production. Most of the proposed research programs feature the goal to extend nuclear structure measurements towards the drip-lines and often reflect in addition a strong astrophysics component.

A pilot ISOL based radioactive beam facility has been in operation at the Université de Louvain la Neuve (Belgium) (http://www.cyc.ucl.ac.be/) since 1989. This facility has contributed significantly to nuclear astrophysics with a program that has focused on the measurement of nuclear reactions in the hot CNO cycles and the break-out from the CNO cycles. The operation of this facility has originated an enormous amount of experience in its 12 years of operation, which has been extremely useful for the next generation projects. There is a broad range of second-generation ISOL based facilities in the design or construction phase using a variety of driver- and post-accelerator combinations. All these projects are presently being funded through a combination of European and National funding agencies. The SPIRAL project at GANIL (France) (http://www.ganil.fr/spiral/) is based on the same principle as the Louvain-la Neuve facility, using cyclotrons as driver- as well as post-accelerator. The construction and performance testing is well ahead and the facility should be operational soon. The design and construction of the EXCYT Project (http://lnsuni2.lns.infn.it/~celona/) at the

INFN/LNS in Catania (Italy) is based on a cyclotron as driver and a 15 MV tandem as post accelerator. The ISOLDE/CERN facility (Switzerland) will provide the location for the REX-ISOLDE experiment (http://isolde.web.cern.ch/ISOLDE/frames/isoframe.html). The 1.4 GeV PS booster will serve as driver and a 2.2 MeV RFQ LINAC as post accelerator. This project will be fully operational soon. In the early planning state is the SIRIUS project (http://www.dl.ac.uk/ASD/NPSG/sirius.html) at the Rutherford Appleton Laboratory or at Daresbury. At RAL it would use the ISIS synchrotron as driver and a 20MeV/u CW-LINAC as post-accelerator. PIAFE-II (MAFF) is a facility presently constructed at Munich (Germany) (http://www.ha.physik.uni-muenchen.de/maff/). Its concept represents a different approach. Born out of the PIAFE project at Grenoble (FRANCE), it uses a high flux reactor (FRM-II) as driver for fission products with a LINAC as post-accelerator. In the longer-range future a next generation ISOL based facility is planned in Europe, EURISOL (http://www.ganil.fr/eurisol/EURISOL1.html) that will carry the European efforts in physics with exotic ion beams well into the century. Considerable advances with ISOL techniques have also been made in Canada. The ISAC facility at TRIUMF (Canada) (http://www.triumf.ca/isac/lothar/isac.html) is presently starting operation and will soon provide one of the major opportunities for nuclear astrophysics experiments with radioactive beams. It offers a unique site for US users prior to the construction of RIA.

The situation is similar with the present status on in-flight facilities for exotic beams. Several new projects are under development or construction worldwide. The possibilities for experiments with exotic beams will multiply by the upgrade of the GSI facility in Darmstadt (Germany) to a next generation in-flight radioactive beam facility, which is presently under debate (http://www.gsi.de/GSI-Future/). The proposal involves the construction of a new 1km-circumference synchrotron ring and accompanying storage rings that will accumulate, store and cool intense high quality beams of secondary exotic nuclei. The upgrade of the radioactive beam capabilities RIKEN to a powerful, next generation in-flight exotic beam facility (http://www-ribf.riken.go.jp/ribf_e.html) has been proposed based on the use of a combination of several superconducting cyclotrons. Additional in-beam fragmentation beam opportunities exist at the Flerov institute in DUBNA (Russia) (http://www.jinr.dubna.su/) where the radioactive beam facility DRIBS is presently under construction.

All these projects are motivated by the scientific goals and questions in nuclear structure and nuclear astrophysics. The US has historically played a leadership role in the development of interest in exotic nuclei and currently operates both ISOL and In-flight exotic beam facilities. With the construction of RIA which unifies the use of ISOL and In-flight techniques, the US will dominate this field over the foreseeable time span since *RIA has capabilities one to two or more orders of magnitude beyond any other current or planned facility in the world.*

5.2   Gamma-Tracking Initiatives

The nuclear structure programs in Europe are centered on the use of large detector arrays like Euroball, new initiatives are forming rapidly to design and build gamma tracking detector arrays within the next few years.

A lot of enthusiasm and support has emerged over the last few years to build a large 4π tracking array, in the spirit of the Euro-ball collaboration (http://nnsa.dl.ac.uk/euroball-home/). There are three types of effort; one is a collaborative effort funded by the European Union as a Training and Mobility of Research (TMR) program (http://www-gsi-vms.gsi.de/eb/html/tmr_groups.html). The second are prototype detector development programs funded by individual countries. The goal of these efforts was originally to have a final design and a proposal in 2002. The third effort, to build a gamma-ray tracking array, was initiated very recently and is part of a major upgrade of the GSI facility in Germany.

The TMR program has a budget of about $1.5M and supports 25 FTE-years of new research effort. In addition, the participants committed 46 FTE-years of existing effort to the program. In total there are 75 researchers contributing to this project in various degrees. So far their efforts in simulation, tracking, and pulse shape analysis have duplicated and verified many of the results of the GRETA development team. In some areas they have made progress beyond the GRETA achievements.

The TMR program does not include the purchasing of prototype detectors. However, individual countries are providing support to do so. A number of detector development projects are presently being funded by Germany, Italy, UK, and France. These projects have a total funding of about $5M for seven types of prototype detectors, which have either been ordered or delivered. Most of them are aiming on small arrays of segmented Ge detectors to be used at the planned radioactive beam facilities, such as Exogam at GANIL (http://www.ganil.fr/exogam/) and Miniball at REX-ISOLDE or MAFF.

The latest development is the plan at the GSI to build a gamma-ray tracking array (AGATA) for its new facility. After several years of study, a design almost identical to that of GRETA (the LBNL concept) was adopted, and represents the first concrete gamma-ray tracking project in Europe. This is achieved without going through the difficult process of coordinating different European efforts and it has a good chance to unite the efforts in Europe. The size of the planned instrument is very ambitious. It will consist of 192 segmented Ge detectors. This has to be compared with 120 Ge detectors currently planned for the GRETA array. The GSI facility proposal including the tracking array could be approved by late 2001. This would put the European tracking array on a time scale at least two years ahead of the US effort, unless the community continues to push forward the effort that established the US as the leader in this development.

5.3　　　　　Low Energy Astrophysics Initiatives

A successful program in nuclear astrophysics requires a broad range of facilities to cover the various stellar nucleosynthesis conditions. While radioactive beam facilities offer the most important opportunities for studying nuclear astrophysics of stellar explosions it has been pointed out before that the study of nucleosynthesis and its consequences in stellar evolution requires the operation of dedicated low energy facilities for high intensity stable beams and for neutron beams.

The research efforts in low energy nuclear physics at the Gamow range is spearheaded by the LUNA initiative (http://www.lngs.infn.it/) in the Gran Sasso underground laboratory. After a very successful operation of a small-scale pilot program, an upgrade of the facility has been approved by the European, Italian and German funding agencies. A new light ion accelerator is presently being installed and will allow the continuation of the program for the next years. The present US programs in low energy nuclear astrophysics will be able to maintain a competitive edge for the short-term future but cannot compete with a dedicated underground facility in the long-range. Alternative approaches like low energy inverse kinematics techniques are being developed in the US but also face severe competition from well-funded European efforts ERNA in Bochum (Germany) (http://www.ep3.ruhr-uni-bochum.de/) and also at Louvain-la-Neuve (Belgium). The combination of inverse kinematics techniques with the background free environment of an underground site would offer premier conditions for improving on the present experimental limitations and deficiencies. To investigate the feasibility for such a long-range facility, however, requires detailed R&D work in the near future.

Nuclear astrophysics with neutron beams has developed to become the premier tool for probing late stellar evolution through the s-process analysis. Neutron measurements can also provide a way for determining p-process reaction rates. While in the past the ORELA facility has been the prime site for nuclear astrophysics with neutron beams, neglect in funding over the last decade has, however, reduced its impact. The center of s-process physics has shifted to the Forschungszentrum at Karlsruhe (Germany) (http://ik3frodo.fzk.de/english.html), which also represents one of the leading institutions in the recent construction of the n-ToF spallation neutron facility at CERN (http://proj-ntof.web.cern.ch/proj-nTOF/). The very efficient European efforts are driven by the close interaction between nuclear astrophysics experimentalists, theorists, and observers. This puts the US nuclear astrophysics community at a rather large disadvantage since the manpower pool has largely diminished over the years. To re-institute a competitive nuclear astrophysics program with neutron beams would require adequate funding for reviving the leading role of the astrophysics research program at ORELA. A modest amount of funding could revitalize the ORELA astrophysics program, bringing it on par with the leading programs in the world. In addition a complementary program should be implemented using the intense neutron beams from the SNS for establishing a long-range future facility for nuclear astrophysics with neutrons.

6.   SUMMARY AND RECOMMENDATIONS

The DNP town meeting in Oakland (November 2000) as well as the previous town meetings on physics with RIA in Durham (June 2000) and on nuclear astrophysics at Notre Dame (June 1999) gave the basis for formulating the long-range goals and plans of the nuclear structure and the nuclear astrophysics community in the United States. The community has driven an extremely successful scientific program over the last decade. The nuclear structure community has been leading internationally in the study of the various modes for nuclear excitation through the use of GAMMASPHERE at Lawrence Berkeley and Argonne National Laboratories. The radioactive beam facility HRIBF at Oak Ridge National Laboratory had its first success in measurements with light radioactive beams and is branching out now successfully into the development of neutron rich radioactive beams. Radioactive beam programs also have been successfully installed at the University of Notre Dame, Texas A&M University, Argonne National Laboratory, and Lawrence Berkeley National Laboratories. The National Superconducting Cyclotron Laboratory at Michigan State University has maintained a leading role in physics far off stability for the last decade. The development of the A1200 fragment separator initiated a series of break-through studies, which solidified the halo structure of light neutron rich nuclei. Fragment separator measurements at Argonne and Oak Ridge National Laboratories as well as at the NSCL at Michigan State University pioneered the study of very neutron deficient nuclei along the N=Z line to probe nuclear structure and nuclear forces at the proton-drip line. The measurement of new superheavy elements at Lawrence Berkeley Laboratory - while still awaiting independent confirmation - have revitalized the excitement about the limits of stability for very massive elements.

Active research programs prosper at smaller university based facilities, which quite frequently spearhead new initiatives by introducing innovative developments. Examples are the development of new spectroscopy techniques and methods for nuclear structure at Yale and Florida State Universities; the use of polarized beams to probe the nature of low energy nuclear reactions for astrophysics at TUNL and Florida State University; the development of a real photon beam for nuclear structure and astrophysics measurements at the free electron laser facility at TUNL. Other examples are the broad application of transfer reaction techniques for probing reactions and reaction mechanisms of astrophysics relevance at Yale, Texas A&M Universities, TUNL, and at the University of Notre Dame. The list should also include the low-funds development of low energy radioactive beams in the US at Notre Dame together with the University of Michigan and the pioneering development of Francium laser trapping at Stony Brook for probing fundamental quantum interactions through its atomic structure.

Based on the successes and developments within the last decade the main interests of the nuclear structure community are in probing the nucleus at the limits of its stability:

- structural evolution as a function of proton-neutron asymmetry
- nuclei at high angular momentum and temperature
- proton-rich nuclei at and beyond the proton drip line,
- neutron-rich loosely bound nuclei,

- superheavy nuclei.

New developments and techniques are necessary to pursue these goals into the future for a better understanding of the nuclear many-body system.

Nuclear astrophysics is characterized by its interdisciplinary nature. As a field it has common interests and overlap with nuclear structure but also with neutrino physics. The number of nuclear astrophysics programs at US universities and national laboratories is growing. Several new faculty positions have been filled or have been advertised in recent years. New research opportunities have opened up at the coupled cyclotron facility CCF at Michigan State, at the radioactive beam facilities HRIBF/Oak Ridge and ISAC, TRIUMF, and at the Free Electron Laser Laboratory (DFELL) at Duke University. New opportunities in low energy nuclear astrophysics emerge through the low energy facility LENA at TUNL and the JINA facilities at Notre Dame. The future goals of the nuclear astrophysics community strongly overlap by nature with the long-range interests in nuclear structure but also have their own unique components due to the diversity of the field. One characteristic interest in nuclear astrophysics is manifest in probing the nucleus at the thresholds of binding energy. This entails:

- the limits of particle stability within the nucleus
- the limits of particle stability of the nuclear landscape i.e., the drip lines
- the interplay between weak and strong interaction processes.

This requires detailed knowledge of the nuclear structure near particle threshold since only through this knowledge low energy reaction rates can be determined reliably. It requires also the understanding of the nucleus at the extreme limits of stability since these limit the reaction path conditions in explosive scenarios.

These goals have successfully driven the field in the past and remain to be the guidelines for the future. To continue with these goals for the short-term and into the long-term future the following recommendations have been formulated and were approved by the Oakland town meeting:

Recommendation #1
The highest priority for the nuclear structure and nuclear astrophysics communities is the construction of RIA as the world's premier facility for the study of exotic nuclei and the pursuit of the associated exciting physics opportunities. These encompass the understanding of nucleonic matter – from the nucleus to neutron stars, – the origin of elements, the quest for the nature of stellar explosions, and tests of fundamental interactions and conservation laws in nature.

The construction of RIA clearly represents the highest goal of the two communities but it is strongly believed that its construction will be a long-range benefit to the entire field of nuclear physics. The unique capabilities of RIA will help to explore the last unknown regions of the nuclear landscape of the nucleus, a few-body system at the limits of stability. This long-range goal complements the parallel initiatives in exploring the quark

structure of the nucleus at Jlab and in probing the quark-gluon phase of nuclear matter at RHIC.

The coupled cyclotron facility at the NSCL provides unique opportunities for the next decade of radioactive beam research for structure and astrophysics. It will also provide an ideal site for exploring the weak interaction processes near the limits of stability. It therefore maintains a unique position for the field. However, to maintain the broad diversity in nuclear structure and in nuclear astrophysics, a continuous strong support and operation of the other existing facilities is necessary. Unlike high-energy physics, nuclear physics cannot stand alone on the basis of a few major facilities. It benefits from and flourishes only through the broad range of complementary experimental opportunities. This insight leads to the second recommendation for the long-range plan.

Recommendation #2
The scientific program of our communities is driven by the vigorous and continuous support of forefront research opportunities at existing national and university laboratories. Based on the scientific potential, the NSCL upgrade was prioritized in the previous Long Range Plan. In order to realize the exciting scientific opportunities now available, the operation and use of the facility should be strongly supported.

University based research groups and laboratories are the lifeblood of our field. Federal investment should be strengthened in order to maintain competitiveness in research and to provide the best possible training for future generations of scientists for our fields and to serve the national needs of our society.

The development of new instrumentation and technologies such as a gamma-ray tracking device represents the key for new discoveries at present and future facilities and should therefore be strongly supported.

A strong nuclear theory program is essential for analyzing and interpreting the accomplishments in experiment and for formulating new directions and goals, in short, for maintaining the momentum into the future. However, nuclear theory is suffering from a depletion of talent, especially in the area of young faculty and new students entering the field. At the present time, we estimate that two nuclear structure theorists below the age of forty have tenure track or laboratory positions in the US. This situation significantly strains the ability to attract young people to the field. Nuclear theory has become increasingly computational in the last few years introducing broad computational issues. Advances in algorithm development and continued access to state of the art national computational facilities remains crucial for many classes of problems including the challenges mentioned above. These issues led to the formulation of the following recommendation:

Recommendation #3
To take full advantage of the exciting science opportunities provided by RIA and the next generation neutrino experiments, a theory initiative is needed. This initiative will invigorate the field of nuclear structure, nuclear reactions, and nuclear astrophysics by

creating new bridged faculty positions, and postdoctoral and student positions. It will also provide additional resources to universities and national laboratories for innovative approaches to the nuclear many-body problem, its astrophysical applications, and the development of a multidimensional supernova model.

The specific needs for nuclear astrophysics data in the very low energy range near the particle threshold require detailed low energy measurements in a background free environment. The possibility of a US underground laboratory offers a potential site for an underground accelerator laboratory. To achieve significant improvements in background reduction and in reaction yield requires major experimental and technical improvements in comparison with present low energy facilities in Europe and the US. The goal for investigating the potential and requirements for developing such a facility stimulated the following recommendation.

Recommendation #4
The resolution of crucial questions in stellar evolution relies on the use of intense low-energy stable beam accelerators. We strongly endorse the effort to explore the advantages and feasibility of a US National underground facility as a site for a low background accelerator laboratory.

The question of the origin of the heavy elements in the r-process and the desire to understand the explosion mechanism of the supernova is closely related with weak interaction and neutrino-physics. Neutrino scattering processes determine the neutrino opacities which revitalize the stalled supernova shock, neutrino induced reaction processes have been predicted to modify the r-process abundance distribution. The verification of these predictions requires the experimental test of the neutrino interaction processes, which in the present models are solely based on theoretical calculations. With the decommissioning of KARMEN at the ISIS spallation source at the Rutherford Appleton Laboratory (http://www-ik1.fzk.de/www/karmen/karmen_e.html), there is no facility anymore in existence to pursue these kinds of measurements. The construction of the next generation neutrino facility ORLaND at the spallation neutron source at Oak Ridge National Laboratory is presently being recommended by the town meeting on "Astrophysics, Neutrinos, and Symmetries". The nuclear structure and nuclear astrophysics communities therefore agreed on the following:

Statement of Endorsement
Closely associated to our interpretation of stellar processes from Sun to supernova is the understanding of weak interaction and neutrino induced processes. Our community therefore endorses the efforts in pursuit of a new neutrino laboratory.

Nuclear structure and nuclear astrophysics represent two important aspects of low energy nuclear physics. The scientific goal of understanding the internal structure and behavior of the nucleus as a finite many-body system and the goal of investigating the impact and signature of nuclear structure and dynamics in astrophysical systems requires a closely related but truly complementary experimental approach. This approach has been extremely successful over the last decades and has formed close connections between the

two communities that have lead to the formulation of the joint recommendations cited above. These recommendations express the close link and overlap with the communities in neutrino physics and fundamental symmetries.

There is a strong belief that the construction of RIA will not only benefit the nuclear structure and astrophysics but it will also offer a unique site for fundamental interaction studies, and may even offer a potential for ultra-cold neutron studies in the future.

Particularly obvious also is the close relation between the fields of astrophysics and neutrino physics. Their common interests in nucleosynthesis – the interplay between r-process and ν-process - and the common interests in understanding the supernova mechanism is reflected in the recommendations on theory as well as on experimental developments. The spirit of these recommendations should help to maintain the close links between the communities and to strengthen their close relationship into the future.