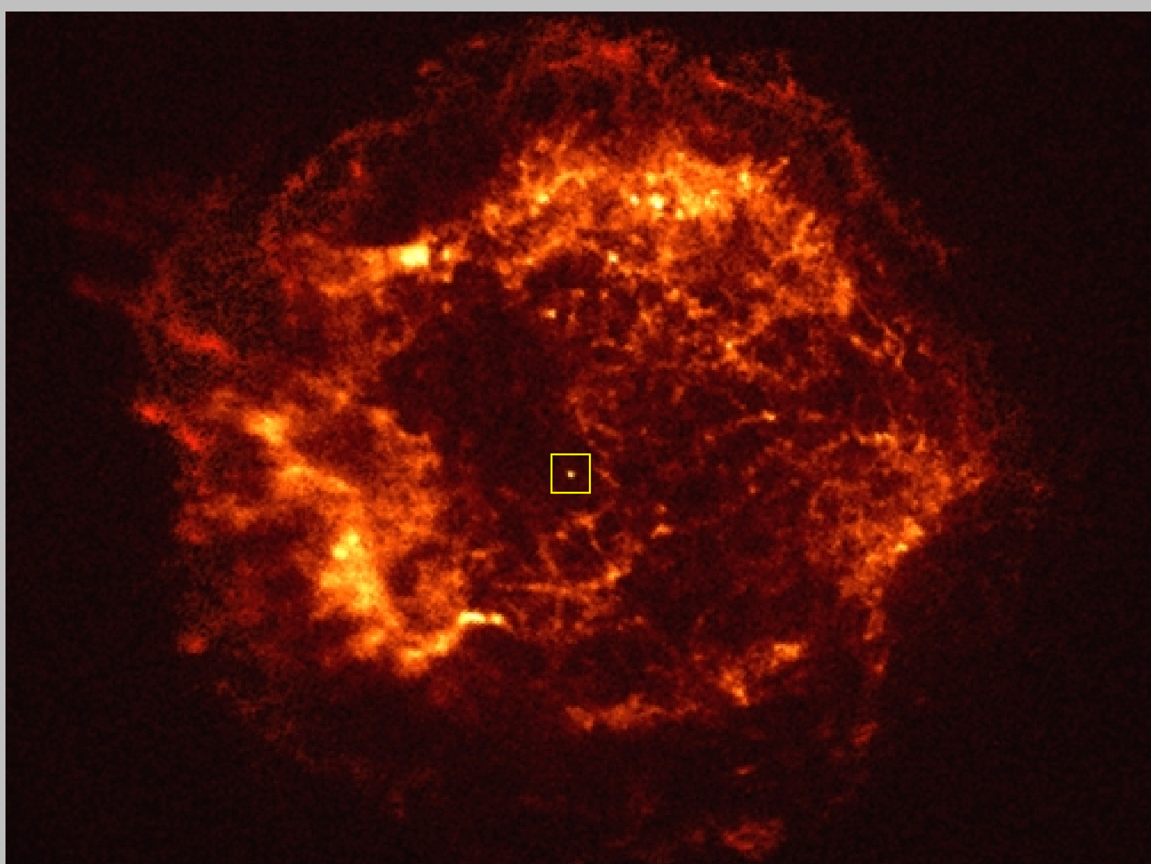
OPPORTUNITIES
IN
NUCLEAR ASTROPHYSICS

ORIGIN OF THE ELEMENTS



30 SEPTEMBER, 1999

OPPORTUNITIES IN NUCLEAR ASTROPHYSICS

Conclusions of a Town Meeting held at the University of Notre Dame
7-8 June 1999

PREFACE

A Town Meeting on Opportunities in Nuclear Astrophysics was held at the University of Notre Dame, on June 7-8, 1999. The meeting was organized by the University of Notre Dame and Michigan State University with the help of a steering committee and was co-sponsored by the American Physical Society's Division of Nuclear Physics. Its goal was to define and summarize the state of the field of nuclear astrophysics and the opportunities for the future of the field. Even though the meeting was organized on relatively short notice, it was attended by over 170 individuals from 68 institutions worldwide, a sign of the great interest in nuclear astrophysics.

The meeting consisted of 18 plenary talks, plus two working group sessions involving a total of 13 working groups. Each of these groups gave a brief presentation of its conclusions and also wrote a synopsis that was used for the preparation of this white paper. The white paper was prepared by a sub-set of the writing committee and was commented upon by other members of that committee, as well as some consultants, when expert advice was required in a particular area.

The Workshop Program, lists of the attendees and of the steering and writing committees can be found in the Appendices.

The White Paper begins with two sections, Challenges in Nuclear Astrophysics and Summary and Recommendations, that are meant to serve as a brief statement of the challenges presented by the field and of how these challenges can be met by the research community. The main part of the document begins with an overview, to provide a guide to what follows, a survey of some of the observational constraints, a detailed discussion of various astrophysical phenomena, and, finally, a discussion of the facilities and equipment needed to address the most important opportunities in nuclear astrophysics.

In order to facilitate reading of the individual sections, redundant information has been provided in many cases.

Cover: First image from the Chandra X-ray Observatory. The image of the Cassiopeia A supernova remnant reveals a fast outer shock wave and a slower inner shock wave. The bright object near the center may be a black hole or neutron star remnant of the supernova explosion.

CONTENTS

I. CHALLENGES IN NUCLEAR ASTROPHYSICS

Introduction

Carl Sagan's statement, "We are made of star stuff," reflects the origin in stellar nuclear processes of the elements that comprise humankind and the whole of the universe, out to the remotest of galaxies. Moreover, the energy on which we depend for life originates in nuclear reactions at the center of the nearest star, our sun.

Our understanding of these processes has developed greatly in the last 75 years. It was known early on that nuclear reactions must provide the energy for the sun. No other processes, chemical or gravitational, could yield the sun's luminosity over its 4.6 billion-year life. More direct evidence for stellar nuclear reactions was the observation of the element technetium in the atomic spectra of distant stars. All isotopes of this element live less than 4.5 million years, and any of them present at the formation of a star would have decayed during the much longer stellar lifetime. The observed technetium must then have been made in the star. In the 1930's Bethe and von Weizsäcker proposed a scenario for nuclear burning, a detailed set of reactions, the CNO cycles, that converted hydrogen to helium in the first stages of stellar evolution. Then, in 1957, the famous paper by Burbidge, Burbidge, Fowler and Hoyle, B^2FH, laid out a scenario for the production of the elements, which was elaborated in the succeeding years. A major development in the 1970's was the big-bang description of the early universe, which explained the formation of the very light elements.

In spite of major efforts in observation, experiment, and theory over the past twenty years, a multitude of challenging questions remain. We are still not certain that we understand hydrogen burning in our own sun and whether the neutrinos it emits reach the earth unaltered. We seem to understand the production of heavy elements by neutron capture in red giant stars, but we are not sure where all the neutrons come from. We analyze precisely the dust of stellar processes in meteoritic inclusions, but we cannot match the results with our present models. We see the characteristic features of the rapid neutron capture process in the galactic elemental abundance distribution, but we are still not sure where and when the process occurs. In the tiny amounts of neutron deficient stable isotopes we see the signature of an enormous gamma flux, but we do not know where or when it occurs. We analyze the outbursts of novae and supernovae, but what we see often disagrees with what was expected. We see gigantic explosions in distant galaxies, but we are only beginning to formulate the detailed descriptions that will allow us to match models with observations.

The challenge of understanding how nuclear processes influence astrophysical phenomena remains. New astronomical observations, new experimental capabilities, and new computational power present an opportunity for an important advance in our knowledge of the cosmos.

Revolution in observation

In the last decade there has been a revolution in astronomical observation over a wide range of the electromagnetic spectrum. Results from satellite based observatories, from the Hubble Space Telescope, and from large-aperture earth-based telescopes have, for example, yielded measurements of the primeval deuterium abundance and of the abundances of elements in very old stars. These observations determine the average baryon density of the universe and indicate that the heavy elements were already being formed in the earliest stellar generations. They may provide insight into the history of nucleosynthesis, star formation and supernova explosions. Abundances observed in the ejecta of nova explosions challenge our models of nucleosynthesis and energy production in novae.

Optical, infrared, and ultraviolet observatories provide only a part of the new information. Observations of gamma-ray lines from the Compton Gamma-Ray Observatory have opened a new field of observation and produced results that will guide our understanding of nucleosynthesis in nova and supernova explosions. The INTEGRAL high-resolution gamma-ray observatory and other future instruments will provide a wealth of data in this regime. Neutrino detectors originally designed to measure the temperature at the center of the sun have indeed verified that nuclear reactions in the sun produce solar neutrinos and have raised the possibility that neutrinos oscillate from one species to another and, therefore, have mass. These neutrino oscillations may have large effects on energy transport and element synthesis in supernovae. Presolar grains, originating in the stellar wind of stars late in their evolution, in supernovae, or in novae have been found in meteorites. The isotopes found in these grains provide detailed information on the processes in individual stellar sites and will help distinguish the results of individual events from the grand average normally seen at the surfaces of stars. A final example is the observed decay of magnetic fields in accreting neutron stars, which is probably affected by the ashes of rapid hydrogen burning on the neutron star's surface.

This summary, far from complete, illustrates the wide range of phenomena that need to be explained and the intimate connections among apparently disparate observations. Fortunately, experimental, computational, and theoretical advances have taken place in both nuclear physics and astrophysics. Together these advances will enable us to obtain key data and to simulate many of these phenomena in the laboratory or computer, greatly increasing our understanding of stars and of the cosmos.

New accelerator facilities

Nuclear astrophysics has traditionally concentrated on measurements that were relevant for understanding stellar evolution and that were carried out at low-energy stable-beam accelerators. Now, needs for data that require new experimental capabilities have opened a new era of measurement.

These measurements are often limited by the extremely low reaction cross sections, which in turn are reflected in the long lifetimes of stars. Only in a single case, $^{3}He + {}^{3}He \rightarrow 2p + {}^{4}He$, have measurements reached the actual energy range of non-explosive stellar processes. Dedicated sources of high-intensity low-energy beams are required to explore other reactions at stellar energies. Locating facilities underground would reduce the large radiation background from cosmic rays and other sources of natural radioactivity, and, in certain cases, make possible measurements at lower energies. Further development of intense heavy ion beams is necessary to explore the low energy range by using beams of heavy projectiles to bombard light targets, the inverse of the usual procedure.

An exceptionally important advance is the development of accelerator systems for the production of beams of short-lived isotopes. Many of the nuclei that are formed in stellar explosions are short-lived, but do live long enough to encounter and react with other nuclei in the hot, dense astrophysical environment. It has been difficult to produce sufficient quantities of these nuclei to carry out meaningful experiments, but in the past ten years modifications of existing facilities have made this possible in selected cases. A new generation of facilities, about to come on-line, will have intensities larger by several orders of magnitude and will greatly expand the range of studies related to astrophysics. Finally, accelerator systems that promise still more intense beams of radioactive ions are under active consideration and are required to study many of the most interesting phenomena.

The development of intense neutron sources will open new fields of investigation. Present sources can provide some of the information necessary for understanding the production of heavy elements in helium burning stars. A new generation of neutron sources in the U.S. (the SNS) and Europe will permit important experiments on radioactive targets. These facilities will also provide a potent source of neutrinos and make it possible to measure neutrino-nucleus interactions that are important in supernova evolution and for calibration of supernova neutrino detectors.

New detectors

Coupled with these accelerator developments has been a revolution in detection apparatus, including large spectrographs with high resolution; mass separators with high selectivity; arrays of silicon, germanium, and scintillation detectors covering the majority of the event space; and enhanced computing power to handle the resulting data streams. As a result, one can employ detectors at accelerators and in space (for cosmic ray observations) that are much more complex than those used previously.

Detectors of solar and supernova neutrinos are a special case. They are large and comparable to accelerators in cost. Yet, the problems they address, the structure of stellar interiors and the nature of neutrinos, are so important that their results are of interest to much of the nuclear astrophysics community and will greatly affect our understanding of astronomical objects.

Still another special case is the LIGO detector for gravitational waves. LIGO may appear to address phenomena far from the interest of nuclear physicists, but will observe the signal from mergers of neutron stars and from supernovae. The nature of the neutron-star signal will depend on the nuclear equation of state that is studied experimentally in nuclear reactions. And predicting the observational signal from an asymmetric supernova explosion requires a variety of detailed information from nuclear physics.

Computational capabilities

Advances in computational capability has occurred just in time to allow us to take advantage of the new observations and nuclear physics results. For example, it may soon be possible to begin study of a supernova explosion in two and then three dimensions with accurate atomic and nuclear physics input. This is a major computational effort, which will eventually require computing power well beyond the present state of the art. Three-dimensional simulations of stellar evolution, supernova explosions, nova explosions, and accretion processes on neutron stars and black holes, are required to model the complex structure of these events and their associated nucleosynthesis and energy generation. These problems will require large investments in calculations of nuclear structure, the nuclear equation of state, neutrino interactions with matter, and hydrodynamics at nuclear densities.

Manpower

As we assess our understanding of the role of nuclear physics in the cosmos, it is necessary to consider also the structural and manpower issues in the field. The national manpower base in nuclear astrophysics, experimental and theoretical, needs to be enhanced to take up these challenges. Many of the analysis tools required to obtain nuclear structure information from experiments remain to be developed, especially for the weakly bound exotic nuclei important in many astrophysical processes. It will require a significant effort to develop the next generation of expertise needed to connect the experimental measurements to the astrophysical needs and to summarize this knowledge in a form useful for astrophysical calculations.

Major challenges

- Our earth and its rich biology depend on the many heavy elements synthesized during stellar evolution and in violent events like supernovae. What are the nuclear processes responsible for nucleosynthesis and when and where do they take place? What are the characteristics – temperature, density, and composition – of the nucleosynthesis sites?

- What is the explanation for the shortfall of neutrinos observed from our sun? Is the current discrepancy entirely the result of new physics beyond our standard theory of electroweak interactions, or does it represent, at least in part, some misunderstanding of the nuclear reactions that power our sun? What new technologies can nuclear physicists and others exploit to measure the entire spectrum of solar neutrinos?

- What drives the spectacular stellar explosions known as supernovae? What are the processes leading to the Type Ia supernovae used as standard candles in determining the acceleration of the universe? How do we correctly model core evolution in core-collapse supernovae? What determines whether a neutron star or black hole is left as a remnant? What is the site of the r-process? Do supernovae produce most of the short-lived gamma-emitting nucleus ^{26}Al that is found widely distributed in the galaxy? Detection of the various neutrino species emitted in such explosions may determine whether massive neutrinos play a central role in cosmology; what detectors might nuclear physicists construct for this purpose?

- What are the processes that led to the isotopic abundances observed in the presolar grains found in meteorites? Can these abundances serve to test models of s-process and r-process nucleosynthesis of the heavy elements in individual stars?

- What is the nature of the explosions that occur in accreting double-star systems? Can developments of present accretion models accurately describe novae, Type Ia supernovae, X-ray bursts, and X-ray pulsars? Do the proposed models for nucleosynthesis on the surface of accreting white dwarfs describe the abundance distributions in the ejecta of novae? How do the microscopic time scales of nuclear reactions affect the time scale of an X-ray burst?

- Does the big bang accurately describe the process that created the lightest elements? Can nuclear cross sections be measured with accuracy sufficient for big-bang calculations of the universal baryon density to provide a stringent cross check of the baryon density obtained from future measurements of the universal background radiation? Can results from the Relativistic Heavy Ion Collider (RHIC) on the nature of the quark/gluon to hadron phase transition shed light on the nature of inhomogeneities in the universal density? Might there exist, in the nucleosynthesis expected from an inhomogeneous universe, evidence of early exotic states of high-temperature hadronic matter?

- Earth is bathed in a sea of cosmic radiation, much of it affected by nuclear processes occurring in our galaxy. How can further measurements of nuclear properties such as lifetimes, gamma-ray lines, and spallation cross sections help determine the origin of this radiation? How can we exploit unstable nuclei as cosmological clocks of past events in our galaxy? What is the origin of the highest energy cosmic rays?

- What exotic forms of nuclear matter exist at the extraordinary densities characteristic of neutron stars? What connections can be established between the observed properties of such stars – masses, radii, rotation rates, and electromagnetic emissions – and the behavior of nuclear matter under exotic conditions? How do the ashes of nuclear reactions involving proton-rich nuclei on a neutron-star surface affect its observable properties?

The following section provides recommendations on how these exciting challenges can be met by the nuclear astrophysics community.

II. SUMMARY AND RECOMMENDATIONS

This is a special time for nuclear astrophysics:

- There is a wealth of new observations that require detailed nuclear data for a credible explanation.
- New accelerators and detection techniques provide an unprecedented and growing capability for providing the needed nuclear data.
- Exponentially growing computational power makes it possible to include the resulting microphysics in simulations of stellar evolution and the sequence of events leading to novae, X-ray bursts, and supernova explosions.

An enhanced program in nuclear astrophysics, theoretical and experimental, will greatly advance our understanding of the cosmos. It will strengthen observational and computational programs by providing the essential foundation necessary for the interpretation and simulation of new results.

The infrastructure in nuclear astrophysics, especially in manpower and theoretical modeling, needs to be enhanced to meet these challenges. The field would benefit greatly from further co-ordination of its efforts and the increased educational opportunities for graduate students. Investment in specialized detection systems is also warranted.

The many connections among astrophysical observables and astrophysical processes demand that nuclear astrophysicists take a broad view of their field. For example, evidence for neutrino oscillations follows from experiments with neutrino detectors for solar and atmospheric neutrinos. These oscillations may strongly affect element synthesis and the evolution of supernovae.

The following are essential ingredients for these enhancements:

Facility needs and uses – see Section XIII
This summary includes needs that have already been identified. Other opportunities and techniques will surely arise in the future.

- A vigorous program of astrophysics studies at the new and upgraded radioactive ion beam facilities. Both fragmentation and ISOL facilities are necessary to obtain the required information.

- Measurements of reaction cross sections with intense beams from low-energy stable-beam accelerators. Background reduction techniques are important. Measurements of reaction rates by indirect techniques and of spallation cross sections with higher energy stable-beam accelerators that provide energies from a few MeV to several GeV/nucleon.

- Operation and construction of solar neutrino detectors and the construction of advanced supernova neutrino detectors for studies of neutrino processes in supernovae.

- Utilization of neutron spallation sources for s- and r-process related experiments and possible measurements of neutrino-nucleus cross sections. Neutron beams from electron linacs and other sources, and gamma-ray beams from free-electron laser and synchrotron radiation sources are also important.

Major equipment needs – see Section XIV**.**

- Highly segmented high-efficiency gamma-ray detector arrays for the study of capture reactions and for the study of the structure of nuclei involved in the s-, r- and rp-processes.

- Large solid angle, good angular resolution, silicon detector arrays for the study of reactions with radioactive beams. These studies will provide masses, resonance energies, level parameters, spectroscopic strength, and decay widths for nuclei involved in astrophysical processes. These detectors require new developments in fast, high-density, low-noise electronics with a low cost per channel.

- High efficiency neutron detection for β-delayed neutron decay measurements. High efficiency and high angular resolution neutron detection for neutrons from charge exchange reactions to determine weak interaction rates in supernova processes and Coulomb-breakup experiments to determine neutron capture rates on radioactive nuclei.

- Magnetic spectrographs with large solid angle acceptances and mass separators with high beam rejection efficiency to provide the high selectivity and resolution required for many experiments. Advanced focal-plane detectors for high rate operation over a broad range of ion charge, velocity, and mass.

- Traps of ions and atoms for studies that require isolated atoms, including measurements of masses and studies of weak interaction properties.

- Dense targets (gas jet and gas cell targets, and liquid and solid targets at cryogenic temperatures), for measurements of small cross sections and for studies with radioactive beams. Development of targets of long-lived radioactive nuclei, especially for studies of s- and p-process nuclei. The expense and availability of rare and separated stable isotopes needs to be addressed.

Manpower

- The infrastructure in nuclear astrophysics, especially in manpower and theoretical modeling, should be strengthened. Additional support for graduate and postdoctoral education is needed. Enhanced and structured collaborations among institutions with different capabilities would contribute greatly to the advance of the field.

Nuclear and astrophysics theory – see Section XII

- Nuclear structure and reaction theory is an essential ingredient of nuclear astrophysics. A major effort is required to connect theoretical calculations to experimental data, to determine astrophysical reaction rates, and to summarize this knowledge in a form useful for astrophysical calculations. A related effort must ensure that the extant experimental data are available to nuclear theorists and astrophysicists for calculation of reaction rates or validation of theoretical models.

- Multidimensional simulations will be an important bridge between nuclear data and astrophysical observations. Group efforts involving both nuclear physicists and astrophysicists are probably the best approach to the simulation of important and complex phenomena such as supernovae. Major computing resources (tera- and ultimately peta-flop scale) will be required.

III. OVERVIEW

For orientation, the following is an overview of the basic phenomena in nuclear astrophysics from the beginning of the universe in the big bang through the evolution of stars. While the broad characteristics of these processes seem fairly well established, many detailed predictions conflict with astronomical observations. Such discrepancies are not surprising, since much of the nuclear physics presently used in calculations of stellar evolution and of nucleosynthesis is taken from rather uncertain extrapolations or theoretical predictions. New experimental and theoretical tools now make it possible to study key nuclear processes in the cosmos and to put the nuclear physics aspects of stellar evolution on a much more solid footing than was possible in the past. Major advances in our understanding of the cosmos are within reach. The nuclear physics issues will be discussed more fully in the chapters following this overview.

The beginning

Our universe is thought to have formed about 15 billion years ago in a hot dense fireball, the big bang. As time progressed, the universe expanded and cooled. After a microsecond, a soup of quarks and gluons condensed into protons and neutrons and the era of nuclear physics began. After another 10 seconds, the universe had cooled to the point that the lightest nuclei, isotopes of hydrogen, helium and a tiny amount of lithium, could form. These nuclei are the ashes of the earliest element-forming processes–all that follows begins with nuclear reactions among the nuclei of these three elements.

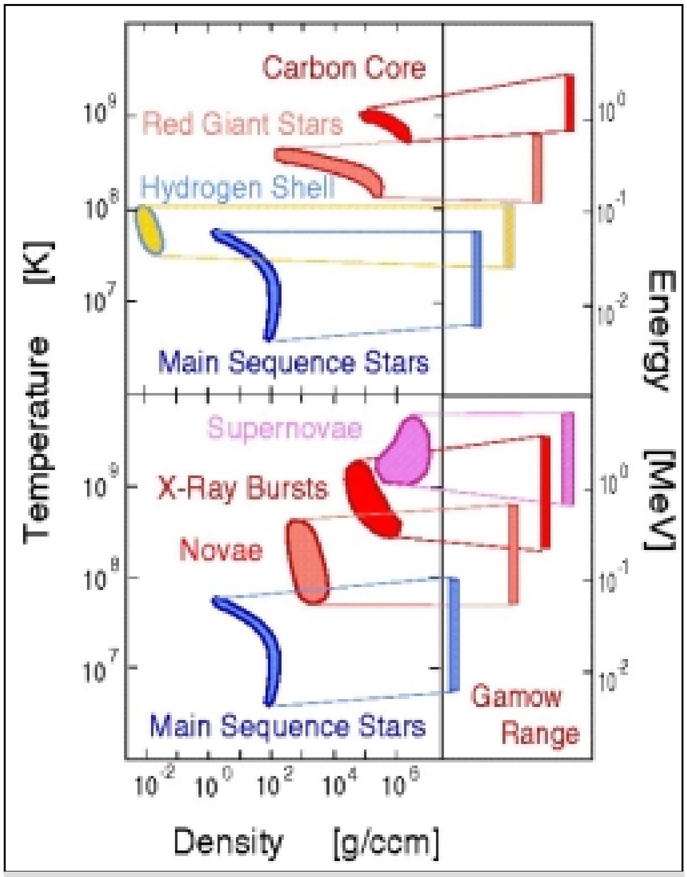
After about 200,000 years, the primordial nuclei and electrons combined. This occurred at a temperature of several thousand kelvins, roughly that at which the most refractory elements melt. It marked the beginning of the epoch in which density fluctuations could begin to grow rapidly, leading to the galaxies and clusters of galaxies that we observe today.

Stellar evolution

The first stars formed from small-scale density fluctuations in regions of relatively high density. Gravitational attraction caused those regions to condense, converting some of the gravitational potential energy into thermal energy, until a temperature high enough to initiate nuclear reactions was reached, about 10 million kelvins, an extremely high temperature by terrestrial standards. These stars then synthesize heavier elements by fusion of their light constituents, thereby releasing energy to stabilize the star against further gravitational contraction.

The central core of a star that is sufficiently massive will evolve through several stages. At each stage, fusing nuclei produce enough energy to heat the core of the star and generate a pressure that successfully opposes the inward force of gravity. When the nuclear fuel is exhausted, the central source of energy is gone and the core contracts under gravity. As the core compresses, gravitational energy is converted into heat until the core temperature is sufficient to ignite the nuclear fuel that powers the next stage. The successive stages characterize stellar evolution, with the nuclear ashes of each stage providing the fuel for the subsequent stage.

For example, the first stage, hydrogen burning, converts four protons into a ^{4}He nucleus. The ^{4}He ashes of hydrogen burning become the fuel for helium burning, where helium nuclei combine to form ^{12}C and ^{16}O. For a star with a mass similar to the sun this is the last burning stage. After throwing off much of its envelope as a planetary nebula, such a star will ultimately become a white dwarf, supported against gravitational collapse by the outward pressure of its (degenerate) electrons and slowly cooling. For more massive stars, subsequent stages of stellar evolution produce successively heavier nuclei from ^{12}C and ^{16}O by carbon, neon, oxygen and silicon burning. These processes are responsible for the synthesis of most of the nuclei from neon to somewhat beyond iron. During some helium burning phases, reactions produce a sufficient number of neutrons to synthesize about half of the heavy elements by the s-process: the slow (s = slow as compared to the beta-decay lifetimes of intermediate unstable capture products) successive capture of neutrons by heavy seed nuclei present in the star. The s-process leads to abundance peaks near nuclear masses of A = 88, 138, and 208.



Summary of conditions in various astrophysical burning phases.
Upper Left: Burning in stellar cores and shells. The extended shapes take into account a stellar mass range of about 1 to 30 solar masses.
Lower Left: Same for several explosive phenomena
Right: The Gamow window for H, He and ^{12}C capture on ^{12}C. This window encompasses the range of center-of-mass bombarding energies which contributes to energy generation and nucleosynthesis, and for which astrophysical reaction rates must be known. It also determines the range of excitation energies for resonances and continuum excitations that are studied by indirect means.

During its final stage of evolution, a massive star forms a core consisting of iron-like (i.e. A ≈ 56) elements, the most tightly bound nuclei in nature. No further nuclear energy source is available, and the outward pressure eventually becomes insufficient to counteract gravity. The iron core collapses and then rebounds when it reaches supranuclear density, ultimately producing a massive explosion, a supernova that blows off the outer envelope of the star. A neutron star or a black hole is left behind. In this process, most of the energy is released as a flood of neutrinos that can be observed in terrestrial detectors. Attempts to understand the supernova process are a major effort of present-day nuclear astrophysics.

Supernovae are probably the sites of the r-process, the neutrino-process, and the gamma-process. The r-process synthesizes the other half of the nuclei heavier than iron by rapid (r = rapid) capture of many neutrons by seed nuclei in an event lasting several seconds. To proceed so rapidly, the process must take place in a dense bath of neutrons and involve nuclei far (20 to 30 neutrons) to the neutron-rich side of stability. It produces abundance peaks at masses around A = 80, 130, and 195. The neutrino-process possibly occurs in the flux of neutrinos that emanates from the nascent neutron star as the high temperature core cools. High-energy neutrinos remove neutrons and protons from the more abundant nuclei and synthesize certain important but rare nuclides. Finally, the gamma-process probably occurs in the hot photon bath near the core of a supernova during explosive neon burning. Photons remove neutrons, protons and alpha particles from heavy seed nuclei and thereby produce rare proton-rich nuclei.

Phenomena in binary systems

More than half of the stars is found in systems of two stars with different masses. After the more massive component has evolved to a white dwarf or neutron star, the system may undergo a variety of dramatic phenomena. This typically occurs when the compact object gravitationally captures (accretes) material from its less evolved companion. For example, the accretion of hydrogen on a white dwarf may ignite a nova explosion in which the brightness of the binary system increases by many orders of magnitude. Related phenomena result from accretion onto a neutron star. Slow accretion is thought to lead to a high temperature explosion observed as an X-ray burst that lasts for tens of seconds. More rapid accretion leads to steady burning and is probably the mechanism for the repetitive emission of X-ray pulsars, seen when the X-ray emitting hot spot rotates into the line of sight of the earth. The energy generation in novae comes from the rapid catalytic burning of hydrogen to helium in the hot-CNO cycles or other cyclic processes; that for X-ray bursts comes from the αp and rp processes, rapid sequences of alpha or proton capture interspersed with beta-decay. These processes involve proton-rich unstable nuclei.

The phenomena described above are repetitive. But rapid accretion on a white dwarf, or merger with another white dwarf may cause its complete disruption, resulting in a Type Ia supernova explosion. These explosions generate much of the iron in the universe, and have served as markers of standard brightness for studies of cosmological expansion rates.

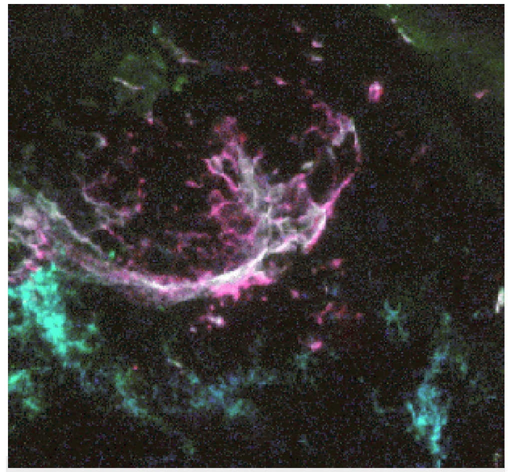
Seeing stellar cores

We cannot use optical telescopes to see the stellar core where nuclear reactions occur; absorption of light limits us to viewing the stellar surface. So it is natural to ask for evidence that nuclear reactions actually occur. Stellar spectra of some stars show lines corresponding to technetium, an element that has no stable form, indicating that the technetium was formed recently in the observed star. Technetium, and other elements, can be brought to the stellar surface by convective processes that dredge up material from deep in the star. Their abundances then provide a measure of the conditions there. Less directly, computer codes that describe stellar evolution and the synthesis of the elements, provide strong evidence that stars evolve and synthesize nuclei in general accord with the processes outlined above. However, this description is far from complete and does not yet describe much of the data that have become available from powerful new observatories. The task of nuclear astrophysics is to make this description fully quantitative by obtaining better nuclear input data and by creating more complete theoretical descriptions.

Recently, a variety of observations has given us glimpses of the conditions in stellar cores and presented new challenges to nuclear astrophysics. Detection of neutrinos from the sun has advanced our understanding of solar processes and of the nature of the neutrinos themselves. Detection of neutrinos from SN1987A gives us confidence that the core-collapse picture of certain supernovae is qualitatively correct; detection of neutrinos from another supernova with an advanced detector would provide a detailed snapshot of what happens in the last few seconds of a massive star's life. Observations of gamma rays from some of the elements made near the core of such a supernova also shed light on nucleosynthesis deep in the supernova. Presolar grains, originating in the stellar wind of stars late in their evolution, in supernovae, or in novae have been found in meteorites and provide information on nucleosynthesis in individual events taking place deep inside stars.

IV. ABUNDANCE CONSTRAINTS ON NUCLEOSYNTHESIS

Nucleosynthesis is the production of the elements that constitute the baryonic matter of the universe. We now understand that nuclear processes, operating both in the early universe and in stars, are responsible for the synthesis of the elements. This universal nuclear history of the matter is written in the compositions of its diverse constituents: stars, interstellar (and intergalactic) gas and dust, meteorites, and cosmic rays.



Hubble Space Telescope image of a supernova remnant known as N132D in the Large Magellanic Cloud. Massive stars synthesize elements in their cores through nuclear fusion. Starting with the light elements of hydrogen and helium, they produce progressively heavier elements, carbon, oxygen, nitrogen, etc., up through iron. At the end of their lives they explode in a spectacular supernova, scattering these elements into space, thereby contributing material to the formation of other stars and star systems. The elements making up life on Earth originated in such stellar ovens. Analysis of the emitted light allows astronomers to explore the details of this nuclear processing. It reveals luminous clouds of supernova debris energized by shockwaves -- singly ionized sulfur appears red, doubly ionized oxygen, green, and singly ionized oxygen, blue.

Credit: J. Morse (STScI) and NASA.

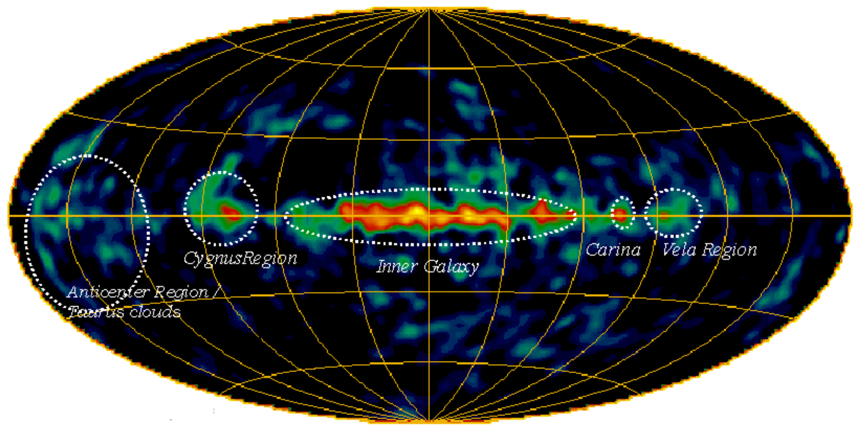
Over the past quarter century, advances in experimental and observational techniques and facilities (e.g. the Hubble Space Telescope, the Compton Gamma-Ray Observatory, the Rosat X-ray Observatory, the Keck telescopes) have made possible accurate determinations of the elemental and isotopic abundances in many astronomical environments. Such studies impose increasingly stringent constraints on models of stellar evolution and nucleosynthesis and help identify critical areas in which nuclear physics input is essential.

Nucleosynthesis sites

Detailed numerical models of nucleosynthesis have served to identify promising sites for the various processes. In the pregalactic nucleosynthesis era, the big bang created the light nuclei ^{1}H, ^{2}H, ^{3}He, ^{4}He, and ^{7}Li. Reactions between nuclei in the interstellar gas and high-energy cosmic rays also form these elements, as may interactions of neutrinos with heavier nuclei in supernovae. Some of the heavier elements (at a concentration of 10^{-4} that of the sun) may have been formed prior to galactic formation. The synthesis of the bulk of the heavy nuclei present in galactic matter, however, is generally attributed to processes in stellar and supernova environments, following the formation of galaxies. Helium burning stars with $M_{sun} < M < 10\ M_{sun}$, are the predominant source of carbon, nitrogen, and roughly half the nuclei heavier than iron. Massive stars ($M > 10\ M_{sun}$) and the associated supernovae (SNe II) produce most of the nuclear species from oxygen through zinc and a significant fraction of the heavier nuclei. Nuclei up to calcium are made primarily in the stable burning presupernova phases, while the iron-peak nuclei are products of explosive silicon burning. Type Ia supernovae produce a substantial fraction of the iron-peak nuclei and some intermediate mass isotopes in explosive carbon, oxygen, and silicon burning processes.

Observational constraints on nucleosynthesis

- Big bang synthesis of the light nuclei ^1H, ^2H, ^3He, ^4He, and ^7Li is constrained by the abundances of these isotopes observed in our galaxy and other galaxies, and in distant gas clouds.



Map, made by the COMPTEL telescope on the Compton Gamma Ray Observatory, of 1.809 MeV gamma rays from radioactive ^{26}Al. Since ^{26}Al has a lifetime of about a million years, the sky image shows the spatial distribution of ^{26}Al producing events integrated over the past million years. Because the galaxy is transparent to gamma rays, the image shows the location of nucleosynthesis throughout the galaxy. Events that produce ^{26}Al appear to lie in our galaxy, with concentrations at the inner galaxy, and near the Cygnus and Vela regions.

Credit: NASA, Compton Gamma Ray Observatory, COMPTEL Collaboration. Courtesy of R. Diehl, MPE Garching.

- Cosmic ray spallation synthesis of the light isotopes ^6Li, ^7Li, ^9Be, ^{10}B, and ^{11}B is constrained by recent studies of lithium, beryllium, and boron abundances in old metal poor stars in the galactic halo.

- Nucleosynthesis via the CNO, NeNa, and MgAl burning cycles is reflected in abundances in globular cluster giants. For example, significant depletions of oxygen are anticorrelated with the abundances of nitrogen, sodium, and aluminum. These observations bear on the nucleosynthetic and convective processes in massive stars.

- Successive phases of carbon, neon, and oxygen burning, associated with massive star and Type II supernova environments, are responsible for the enhancements of the α-elements O, Ne, Mg… compared to the Fe observed in old stars located in the halo of our galaxy. This overproduction of α-elements in Type II supernovae must ultimately be compensated for by other processes, presumably with material rich in Fe from Type Ia supernovae.

- Nucleosynthesis processes in novae are constrained by the abundances of many elements with masses $A < 35$, found in nova ejecta (see Section VIII).

- Recent studies of extremely metal-deficient halo stars find r-process abundances in the mass range from barium through the actinides that are closely proportional to solar system r-process abundances. Data on some of the same stars show that r-process nuclei with $A < 130$ are not produced in solar proportions relative to the heavy r-process elements. This could mean that r-process production of light nuclei is sensitive to the details of a specific site, or it may be evidence that multiple r-process sites are contributing.

- Nuclei in the iron-peak region are probably the products of explosive nucleosynthesis in core-collapse and Type Ia supernovae. Observations of gamma rays from Supernova 1987A revealed that approximately 0.075 M_{sun} of ^{56}Ni was ejected with an isotopic ratio ^{57}Ni/^{56}Ni that is approximately 1.5 times that seen in the solar system. Gamma rays from ^{44}Ti have been detected from the remnant of the Cas A supernova. These results can be used to determine how much material was ejected into the interstellar medium (compared to that accreted on the supernova remnant) by a supernova explosion, as well as the conditions deep inside the exploding star.

- A variety of sources can produce the ^{26}Al in the galaxy. A map of the distribution of gamma rays from ^{26}Al is shown in the figure in this section. When more information is available for the distribution of ^{60}Fe gamma rays, a comparison of these distributions should strongly constrain the nature of the sources of ^{26}Al.

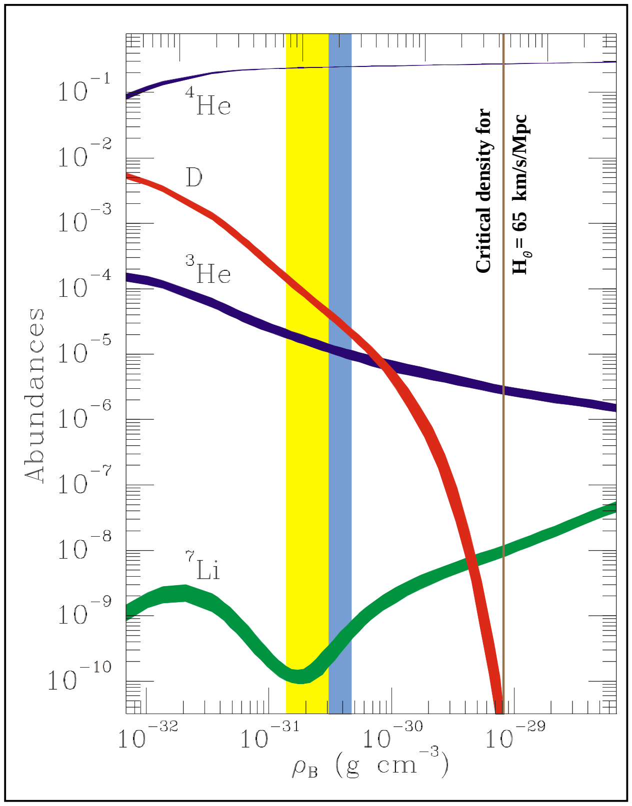
- Presolar grains, tiny (1.6 nm to 20 μm) inclusions found in meteorites, yield isotopic abundances corresponding to individual astrophysical events, some apparently from s-process sites and planetary nebulae, and others from supernovae. These abundances serve to test models of s-process nucleosynthesis in shell-helium burning (AGB) stars and of explosive burning in supernova shock fronts.

These great advances in observation draw attention to the fact that we have far to go to reach a real understanding of the processes involved. Many details will be given in the remainder of this document. For example: we do not know the sources of the cosmic rays, we do not understand the origin of Type Ia supernovae, we cannot consistently calculate a SNe II explosion, we do not know where the r-process takes place, and we do not yet have a convincing explanation of why we observe fewer neutrinos than expected from our sun.

V. NON-STELLAR EVENTS

The big bang

Our universe began about 15 billion years ago in the big bang, a hot, dense expanding fireball. Early in the expansion, the effects of quantum gravity, grand unification of forces, and inflation were the most relevant; it is in this era that the dominance of baryons over anti-baryons was first established. There is a general understanding of what occurred at these early times, but many issues are still unsettled. After about a microsecond, nucleons and other hadrons condensed from a soup of quarks and gluons during the quark/gluon to hadron phase transition. After about 10 seconds black body photon energies were small enough, compared to the binding energies of the lightest nuclei, that synthesis of the light elements began. This era is the domain of nuclear physics and astrophysics. Research at the Relativistic Heavy Ion Collider (RHIC) may help establish the nature of the phase transition leading to hadrons. Studies of the reactions that create the elements have led to an accurate determination of the average amount of normal matter (baryons) in the universe.



Summary of big-bang production of the light elements; predicted abundance is plotted against the mean density of baryons. The widths of the curves indicate the theoretical uncertainties, and the vertical yellow band is the consistency interval in density where the predicted abundances of all four light elements agree with their measured primeval abundances. The blue band in the consistency interval corresponds to a recent determination of the primeval deuterium abundance. The consistent value is larger than the amount of luminous matter seen in stars and galaxies and smaller than the total value of the mass seen in galactic clusters. This indicates that there must be both baryonic and non-baryonic dark matter in the universe.

Adapted from D.N. Schramm and M. Turner. Reviews of Modern Physics **70**, 303 (1998). Figure courtesy of K. Nollett.

This result follows from a comparison of the number of nuclei synthesized in the big bang, as a function of the average baryon density parameter Ω_b, to their observed primordial values. Determination of the primordial abundances requires both careful observation and an understanding of how galactic evolution might have altered the observed abundances. It is a triumph of modern cosmology that the predictions for ^{2}H, ^{3,4}He and ^{7}Li, which range over nine orders of magnitude, agree with observation at nearly the same value of Ω_b. This serves as evidence for the big-bang paradigm and provides a measure of the universal density of baryons. The latest estimates give a value $\Omega_b \approx 0.05$, where $\Omega = 1$ is the highest density that allows the universe to expand forever. Important conclusions follow from combining this result with other evidence: that there are both normal (baryonic) and exotic (non-baryonic) types of dark matter, and that the number of light neutrino species is less than 3.2. The big-bang limit on neutrino species applies to neutrinos with a mass less than about 1 MeV and hence provides somewhat different information than the value based on the shape of the Z^0 resonance of particle physics.

We are now entering an era in which more precise predictions of big-bang nucleosynthesis will be needed, presenting a real challenge to nuclear astrophysicists. Determinations of Ω_b depend most critically on the measured deuterium abundance. Better deuterium measurements will be made, and the uncertainties in the nuclear reaction rates leading to deuterium will then dominate the uncertainty in $\Omega_{b.}$ An independent estimate of Ω_b will soon be available from measurements of the cosmic microwave background; comparison with an accurate value from big-bang nucleosynthesis will be a powerful consistency check on the big-bang model. It may then be possible to determine the universal density from the deuterium abundance observations alone and to predict the big-bang production of ^{3,4}He and ^{7}Li. These abundances can then be used to test models of stellar evolution. For example, following this approach for ^{7}Li, the current big-bang model predicts an abundance larger than observed. This result can be compared with the predictions of Li depletion on the surfaces of stars to provide a unique test of stellar models.

Nucleosynthesis in the big bang involves sequences of nuclear reactions among all the light nuclei. More accurate cross sections are needed for a number of these reactions to improve the accuracy of predicted element production in the big bang. For deuterium synthesis the required cross sections are (in order of importance): d(d,n)^{3}He, d(p,γ)^{3}He, d(d,p)^{3}H and p(n,γ)d. For ^{7}Li synthesis important reactions (in addition to those for deuterium) are: ^{3}He(^{4}He,γ)^{7}Be, ^{7}Li(p,n)^{7}Be and ^{3}He(d, p)^{4}He. The temperatures involved are sufficiently high that cross section measurements are usually performed over the entire relevant energy range, which varies from tens of keV to hundreds of keV. Such energies are available at a variety of modern experimental facilities.

It is an open question as to whether a signature of the quark/gluon to hadron phase transition can be found in the light-element abundances. If the transition is sufficiently sharp (first order), density inhomogeneities may develop and change the nature of the nucleosynthesis. Calculations indicate that the constraint of fitting the observed abundances does not allow average baryon densities greatly different than those of the standard big bang. However, nuclei that are not made appreciably in the standard big bang – beryllium and boron, for example – may be produced, providing observational signatures for inhomogeneities in the early universe. Rates for reactions involving short-lived nuclei, of which the most important involve ^{8}Li, are required to address this open question. For example, the ^{8}Li(α,n)^{11}B reaction is thought to lie on the dominant pathway for production of all nuclei heavier than ^{11}B. Further studies, both experimental and theoretical, are required to determine the reactions that are the most important for production of heavier nuclides, and the clearest observational signatures of possible inhomogeneities.

Galactic cosmic rays

An enigmatic population of relativistic ions and electrons, the Galactic Cosmic Rays (GCRs), fills interstellar space in our galaxy. Models of GCR propagation based upon known breakup cross sections, and the fraction of radioactive products that survive, can be used to determine the average age of the GCRs, as well as the average density and total amount of material they pass through during their lifetime in the galaxy. The cosmic rays also contribute to the synthesis of the light elements, especially Li, Be and B, via breakup (spallation) reactions on ^{4}He, C, N and O nuclei in the interstellar medium. Other mechanisms also produce these nuclei: ^{7}Li is made in the big bang, and ^{7}Li and ^{11}B are potentially made by the neutrino-process in which neutrinos break up ^{4}He and ^{12}C in the helium and carbon shells of supernovae. The breakup products are processed by nuclear reactions in the hot environment, and the resulting ^{7}Li and ^{11}B are eventually ejected into the interstellar medium. It is important to understand the contributions of these various mechanisms to determine whether we have a consistent picture of the process. This is not yet possible and uncertainties in the cross sections for production in the cosmic rays contribute to the problem. Breakup cross sections for C, N and O on hydrogen and helium are reasonably well known, but there are few measurements for important two-step processes, such as the breakup of C to form B, which then breaks up to form Be or Li.

The origin of the cosmic rays has remained obscure despite decades of research. Recent high-precision measurements of GCR composition on the Ulysses, ACE, and Mir spacecraft have apparently ruled out two possible sources: fresh supernova ejecta and solar-like sources with preferential acceleration of easily ionized elements. Expected measurements from next generation detectors (including the Advanced Cosmic-ray Composition Experiment for Space Station (ACCESS), and the Extremely Heavy Cosmic-ray Composition Observer (ECCO)), promise to explore the limits of the supernova shock acceleration mechanism, to measure the GCR abundances of all individual elements in the periodic table, and to provide an independent GCR age using actinide clocks. The source of the highest energy cosmic rays, with energies in excess of 10^{20} eV is also uncertain–it is not clear whether they originate in the galaxy.

Accurate spallation cross sections are required to determine the elemental and isotopic abundances of the cosmic ray source from cosmic ray abundance observations, and to measure energy-dependent flight distances and flight times (using radioactive secondary nuclei as clocks) of the cosmic rays. Our understanding of these aspects of the cosmic ray composition is presently limited by the inaccuracies of the cross sections that affect them and in some cases by the lifetimes of the clock nuclei. The most important measurements are for hydrogen targets and include spallation cross sections leading to individual isotopes for ^{56}Fe, ^{60}Ni, and ^{28}Si at bombarding energies between about 200 and 2000 MeV/nucleon; spallation cross sections to individual elements for Sr, Ba, and Pb between 1 and 10 GeV/nucleon; and elemental spallation and fission cross sections for uranium at several GeV/nucleon.

VI. NUCLEOSYNTHESIS AND STELLAR EVOLUTION

Stellar evolution is characterized by a series of long-lived stable periods separated by phases of rapid core contraction. The stable phases are brought about by quiescent nuclear burning deep in the stellar interior, which produces sufficient energy to stabilize the star against gravitational collapse. The duration of the stable periods and the associated element synthesis and energy generation depend upon the rates of the active nuclear reactions. After the nuclear fuel is depleted, the core contracts, and is heated by the release of gravitational energy until it reaches the temperature and density necessary to trigger a burning phase fueled by the ashes of the preceding phase. During these contraction phases, nuclear burning develops in thin shells surrounding the contracting core. Steep temperature gradients result, and can cause rapid convection that dredges up freshly synthesized material from the burning zones into the stellar atmosphere where it can be observed.

A star forming region DEM192 in the Large Magellanic Cloud. After a star is born, it may develop a strong wind which pushes away nearby gas; it may be so hot that the emitted light boils away nearby dust and gas, or it may be so massive that it evolves quickly to form a supernova and catapults its elements back to the interstellar medium.

Credit: C. Smith (U. Michigan), Curtis Schmidt Telescope, CTIO, Chile.

Although these complex processes appear to be understood in broad outline, there are severe and often unacknowledged problems, due in part to the lack of reliable experimental reaction rates. Only one reaction, $^{3}He(^{3}He,2p)^{4}He$, has been studied at the energies important for non-explosive stellar burning. All other rates are based on extrapolations of experimental laboratory data down to stellar energies. The uncertainties of these extrapolations may span an order of magnitude or more in some cases, with major consequences for nucleosynthesis and energy generation. For example, recent observations of ^{7}Li, ^{23}Na, and ^{27}Al in the stellar atmospheres of red giant stars have proven to be difficult to explain, and the isotopic abundances found in meteoritic inclusions, condensed in the wind of shell-helium burning (AGB) stars and planetary nebulae, don't match the anticipated ratios. Such open questions require continued experimental and theoretical effort.

Stellar-core burning

During hydrogen burning in the so-called main sequence stars, four hydrogen nuclei fuse to form helium in the stellar core. For stars of less than 1.5 solar masses the fusion process is dominated by the pp-chains. The slowest reaction, p + p fusion to form deuterium, determines the lifetime of the hydrogen burning phase. This reaction is mediated by the weak interaction, and its rate is based only on theoretical calculations – it is too small to be determined experimentally. Other processes of interest are the $^{3}He(\alpha,\gamma)^{7}Be$ and $^{7}Be(p,\gamma)^{8}B$ capture reactions. A detailed knowledge of these rates is necessary to predict the solar neutrino flux and to interpret results from solar neutrino detectors (see Section XI).

For more massive stars hydrogen burning proceeds by the various CNO cycles, which convert hydrogen to helium, and carbon and oxygen to nitrogen in the stellar core. The rate of energy generation in the CNO cycle is determined by the slow $^{14}N(p, \gamma)^{15}O$ reaction, which has sizeable uncertainties. This uncertainty results in significant uncertainties in the ages obtained for old globular clusters. Convective mixing remains a difficult problem for stellar models. In addition to the carbon isotopes, the abundances of the oxygen isotopes appear to be sensitive functions of mixing. The relevant reactions, particularly those involving ^{17}O, require re-examination.

A period of core helium burning follows, and converts helium to ^{12}C and ^{16}O. Its lifetime depends on the triple-alpha reaction, the sequential fusion of three ^{4}He particles to form ^{12}C. Because He-burning reactions are typically harder to measure than H-burning reactions (due to the larger Coulomb-barrier and higher background levels), some basic questions concerning He-burning remain unanswered. The essential features of the triple alpha reaction are understood: the rate is based on the level parameters of the second excited 0^+ state in ^{12}C. Other effects, often not taken into account are tail-contributions of the resonance, interference effects with other 0^+ levels, and contributions from higher energy resonances. Such effects may become important for determining X-ray burst ignition or for modeling Type Ia supernovae (see Section VIII). The $^{12}C(\alpha,\gamma)^{16}O$ reaction helps to determine the mass of the core following He-burning, and the C/O ratio which greatly influences the future evolution of the star. For these reasons this reaction is of central importance to stellar evolution. After years of concerted effort, the rate for this reaction is still not known with anywhere near the required accuracy of about 20%. Similar arguments and difficulties exist for the subsequent $^{16}O(\alpha,\gamma)^{20}Ne$ reaction where the rate is also not well known in the stellar energy range.

Helium burning is also responsible for producing the neutrons that synthesize heavy elements in the s-process. The rates of the relevant reactions, $^{13}C(\alpha,n)^{16}O$ and $^{22}Ne(\alpha,n)^{25}Mg$, and the associated reactions $^{14}N(\alpha,\gamma)^{18}F$ and $^{18}O(\alpha,\gamma)^{22}Ne$ are based only on measurements well above the stellar energy range and therefore require further study. The uncertainties in these rates are at least three orders of magnitude at stellar temperatures, with possibly significant consequences for our present interpretation of s-process nucleosynthesis within the framework of stellar models (see Section IX).

The subsequent heavy-ion burning phases depend on the nucleosynthesis of ^{12}C and ^{16}O during the He-burning phase. Both the ensuing fusion reactions themselves, $^{12}C+^{12}C$, $^{12}C+^{16}O$, and $^{16}O+^{16}O$, and capture of protons and alpha particles by the fusion products are important. Neither the fusion processes, nor the subsequent proton and α capture reactions are sufficiently well known for reliable modeling of the later phases of stellar evolution.

In the burning stages that follow oxygen burning, nuclei heavier than calcium are synthesized in the presupernova phase of the star. Nucleosynthesis increasingly occurs in a state of full or partial nuclear statistical equilibrium in which nuclear binding energies and partition functions mainly determine the synthesized abundances. So long as the "freeze-out" is sufficiently rapid, individual rates are not very important. This is not to say that rates on particular species in the Fe group can be ignored. When a system cools from statistical equilibrium, it falls out of equilibrium at a temperature of roughly three billion kelvins. After this point, the species produced will again be sensitive to individual reaction rates. Rates for electron capture also begin to become important during the equilibrium phase.

Stellar shell burning – Red Giant and AGB stars

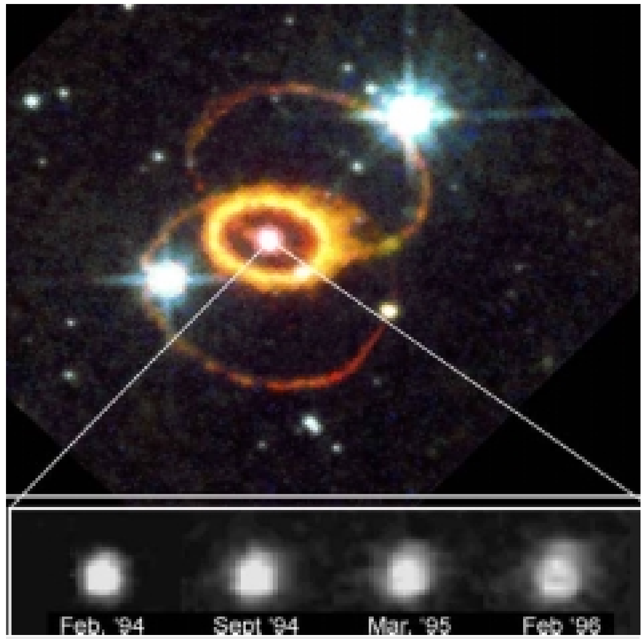
Hydrogen shell burning around an inert helium core powers the initial Red-Giant phase of stellar evolution just before the onset of core-helium-burning. In general, nucleosynthesis in hydrogen and helium burning shells takes place at higher temperatures but lower densities than the corresponding core burning. As a result, higher Z nuclei are involved in the process. Besides the CNO cycles, reactions involving the Ne-Na and the MgAl cycles can take place in hydrogen burning shells. Strong convective mixing processes bring the freshly synthesized material to the stellar surface. There it is directly accessible to observation and offers one of the few opportunities to test nucleosynthesis models directly.

Rapid convective processes are of particular importance in the intermittent shell burning cycles of core-carbon-burning stars in their asymptotic giant branch phase (AGB stars). In stars with $M < 4\ M_{sun}$, helium flash induced pulsations lead to strong envelope mixing. Fresh fuel is transported to the burning zones while the synthesized products are dredged up from the burning zones to the outer atmospheres of the star and substantially modify the surface composition. Radiation driven winds eject the material into interstellar space, triggering the formation of planetary nebulae. The helium burning shell is the site for the main component of the s-process, thought to be driven by the $^{13}C(\alpha,n)^{16}O$ and $^{22}Ne(\alpha, n)^{25}Mg$ reactions (see Section IX).

There are considerable discrepancies, owing partly to the treatment of convective processes in one-dimensional models and partly to the lack of reliable experimental reaction rates for proton and alpha capture in the Ne to Si range. Until these rates are better known, it will be difficult to isolate and resolve the astrophysical uncertainties.

VII. SUPERNOVAE

Supernovae are the most spectacular objects in the cosmos. A star brightens by many orders of magnitude, sometimes becomes visible to the naked eye during daylight, and leaves behind striking remnants such as the Crab Nebula. There are two principal types of supernovae. Core-collapse supernovae, for example, Types Ib, Ic, and II supernovae, result from the collapse of the iron core of a massive star at the end of its life. Type Ia supernovae are probably triggered either by the merger of two white-dwarf stars or by fast accretion onto the surface of a single white dwarf. Supernova explosions are responsible for the synthesis of the majority of the elements.



Hubble Space Telescope image of Supernova 1987a. In February 1987, light reached Earth from a star which exploded in the nearby Large Magellanic Cloud. Supernova 1987a remains the closest supernova since the invention of the telescope. The explosion catapulted a tremendous amount of gas, light, and neutrinos into interstellar space. When observed by the Hubble Space Telescope (HST) in 1994, large rings were discovered whose origin is still mysterious. More recent HST observations shown in the inset have uncovered the expanding fireball from the exploding star. These high resolution images resolve two blobs flung out from the central explosion.

Credit: C. S. J. Pun (GSFC) & R. Kirshner (CfA), WFPC2, HST, NASA.

In addition, the assumption that Type Ia supernovae are standard candles, with a determinable intrinsic brightness, lies behind recent evidence that the expansion rate of the universe is increasing. The following discussion concentrates on core collapse supernovae. However, it is also of great importance to understand the Type Ia mechanism better, and to determine the reliability of the standard-candle assumption.

One of the most important and challenging problems in nuclear astrophysics is to understand the explosion mechanism of core collapse supernovae and the associated element synthesis. Core collapse supernovae are extraordinary events, releasing 10^{53} erg of energy in the form of neutrinos of all types at the staggering rate of 10^{57} neutrinos per second (see Section XI), and generating the conditions for the synthesis of many new nuclei. The explosion ejects these nuclei into the interstellar medium, where they can be incorporated into new stellar systems like our own, forming the basis for life itself. Left in the wake of the explosion is a relativistic object, a black hole or a neutron star that may contain new forms of hadronic matter. As a result, a supernova is a unique cosmic environment for studies of nucleosynthesis; neutrino properties; and nuclear matter at extremes of density, temperature, and neutron to proton ratio.

The core collapse mechanism

In our current picture of the supernova process, an outgoing shock wave – formed when the iron-like core of a massive fully evolved star collapses gravitationally and rebounds at high (supranuclear) densities – stalls as a result of energy losses due to nuclear dissociation and neutrino emission. A few seconds later, the shock is re-energized by the intense neutrino flux emerging from the protoneutron-star at the stellar center. The shock induces explosive nucleosynthesis in the outer layer, leading to the observed explosion. The observation of neutrinos from SN1987A gives us some confidence that this picture is at least qualitatively correct. Yet this attractive idea has not borne fruit–supernovae simulations have not consistently resulted in explosions. It is not clear where the fault lies: in inaccurate knowledge of the nuclear structure physics involved and of the nuclear equation of state, or in the manner by which energy is transported by neutrinos, or in the absence of multidimensional calculations that can fully take into account the relevant microphysics.

To remedy this situation, computer simulations involving accurate multidimensional, neutrino-energy-dependent radiation transport and radiation hydrodynamics must be supported by commensurate improvements in the microphysics. This will require the integration of state of the art supernova simulation and nuclear structure computation to model both the explosion mechanism and supernova nucleosynthesis. Only a consistent treatment of the explosion and its nucleosynthesis will allow the use of observational constraints such as isotopic abundances, gamma, and neutrino fluxes, to obtain information on the explosion mechanism. Challenges include modeling lepton number losses during the infall stage, the stellar core equation of state, post-core-bounce neutrino heating, and the nucleosynthesis that takes place in the ejecta.

Toward a solution

There is great promise for carrying out such calculations because of imminent advances in our knowledge of nuclear properties and the other microphysics required for accurate theoretical modeling, coupled with rapidly growing computing power and new observations that will constrain the theoretical results. For example:

- Radioactive and stable ion beams from new and upgraded facilities will provide information on nuclear structure and reactions that affect all stages of the explosion, from the evolution of the presupernova star, to reactions in the ejecta resulting from the explosion. They will also provide benchmarks to validate the theoretical calculations that in the end must provide the many hundreds of nuclear properties needed to describe the explosion.

- Observatories such as the Keck telescopes, the Hubble Space Telescope, the Compton Gamma-ray Observatory, and their successors, will provide a flood of new data at many wavelengths on the composition and morphology of supernova ejecta. Measurements of heavy elements in extremely metal-poor stars and of the time evolution of Li, Be, and B abundances will directly test the r-process, the ν-process, and other nucleosynthesis mechanisms that supernova simulations attempt to model. Individual grains of supernova material are being harvested from meteorites. These observations will provide a signature of the explosion mechanism, the associated nucleosynthesis, and the subsequent cooling of the ejecta.

- Neutrino detectors such as Super-Kamiokande and the Sudbury Neutrino Observatory promise thousands of neutrino events from the next galactic supernova and will provide detailed neutrino ``light curves" for comparison with supernova models. An advanced detector may also provide discrimination among different neutrino types. KARMEN, LSND, and other low-energy neutrino experiments have demonstrated the feasibility of measuring inclusive and exclusive neutrino-nucleus cross sections that will help calibrate these advanced detectors.

- Gravitational wave observatories such as LIGO and VIRGO will bring additional and complementary information from deep within the explosion, allowing us to learn about asymmetry in the stellar core collapse and the different modes of supernova convection thought to play a role in the explosion mechanism.

- Neutrino oscillations may play a central role in supernova evolution. A fundamental understanding of the explosion mechanism coupled with detectors that measure the fluxes of different neutrino species from the next galactic supernova will allow us to extract information on neutrino physics that is not otherwise accessible.

- The advent of large-scale computing resources will make it possible to tackle multidimensional simulations with realistic neutrino transport.

Supernovae of Type Ia

Supernovae of Type Ia have assumed an important role in cosmological studies. Their great brightness, and the apparent ability to calibrate their luminosity phenomenologically, makes them useful for measurements of cosmological distance and expansion rates. Unfortunately, we lack a full understanding of the explosion mechanism, which casts some doubt on their calibration. Several mechanisms have been proposed, but a comparison of predicted and observed spectra points towards thermonuclear explosions on accreting white dwarfs with high accretion rates. The accreted hydrogen is rapidly converted to helium and subsequently, by He burning, to carbon and oxygen which accumulates on the surface of the C/O white dwarf. If the growing mass of the white dwarf exceeds the Chandrasekhar mass of about 1.4 M_{sun}, contraction sets in, carbon ignites by fusion reactions with screening enhancements, and a thermonuclear runaway starts at the center. Expansion and convective instabilities lead to burning-front propagation via heat convection, which accelerates, presumably to supersonic speed, and finally turns into a detonation, causing a complete disruption with no remnant left behind.

Required nuclear physics information

Type Ia and core-collapse supernovae share a strong dependence on the rate, $r_{12\alpha}$, of the $^{12}C + \alpha \rightarrow ^{16}O + \gamma$ reaction. This rate determines the C/O ratio of a white dwarf, and hence the peak luminosity obtained from the runaway thermonuclear burning that powers Type Ia supernovae. Whether Type Ia supernovae can serve as standard candles may, therefore, depend on $r_{12\alpha}$. In the case of core-collapse supernovae, the size of the iron-like core (and the energy dissipated by the outgoing shock wave in nuclear disintegration) depends on the predominance of C or O in presupernova evolution and hence on $r_{12\alpha}$. As shown in Section XIII, a variety of facilities can contribute to the study of this important reaction.

The rates of weak interactions such as electron capture and beta-decay in hot dense environments are also important in both cases. These processes affect the electron pressure and the neutron to proton ratio of the precollapse core. In the case of core collapse supernovae, estimates indicate that successive electron capture and beta-decay, together with the associated neutrino emission, might lower the temperature of the iron-like core by as much as 10%. High-energy fragmentation facilities with beam energies greater than about 120 MeV/nucleon, can provide experimental information on weak interaction rates for the most important radioactive participants (e.g. ^{56}Ni) through studies of hadronic charge exchange with beams of radioactive nuclei bombarding light targets. These are similar to earlier (p,n) reaction studies, but done in inverse kinematics so as to study radioactive nuclei.

For core-collapse supernovae, two further inputs are needed. Required information on inelastic neutrino-nucleus interactions for core collapse and protoneutron-star cooling could be provided by studying inelastic scattering of 100-200 MeV/nucleon beams of hydrogen or ^{6}Li from stable nuclei of interest. One must choose conditions that mimic the neutrino-induced processes: small momentum transfer and quantum number selection of axial processes. For unstable nuclei, one would bombard hydrogen or ^{6}Li targets (the quantum numbers of ^{6}Li states can be chosen to select only axial transitions) with radioactive beams. Information on the nuclear equation of state from sub- to supranuclear densities could be provided by studies of nucleus-nucleus reactions in the 100-500 MeV/nucleon range, using radioactive beams to adjust the neutron to proton ratio of the reactants. Future detection of supernova neutrinos may provide unique information on neutrino interactions in hot dense matter. For the description Type Ia supernovae, an accurate description of the ^{12}C + ^{12}C reactions that initiate the process leading to detonation is required.

For supernova nucleosynthesis, experimental and theoretical results are needed for properties of nuclei on and near the r-process path, for neutrino-nucleus interactions relevant to the neutrino-and the r-process (see Section IX), and for the rates for explosive nucleosynthesis in supernova ejecta. Information on the neutrino-nucleus reaction can be obtained from hadronic charge exchange and inelastic scattering as described in the previous paragraph or, in the future for stable nuclei, by direct measurement of neutrino induced processes.

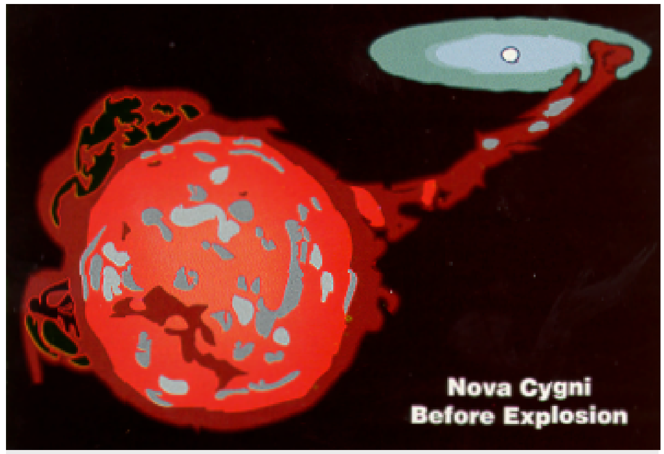
Shock-induced explosive processes in supernova ejecta often occur in statistical equilibrium where the resulting composition depends mainly on the nuclear masses and stellar variables. But there are also cases where equilibrium is not achieved and nuclear reaction rates at high temperatures must be known, in most cases for unstable nuclei. The inner stellar zones are dominated by explosive Si-burning, which synthesizes proton-rich nuclei such as ^{56,57}Ni and ^{44}Ti. Direct observation of these radioisotopes in supernova remnants, via their gamma rays, yields information about the thermodynamic conditions of the innermost ejected material and provides an important test of supernova model predictions. The reactions leading to these nuclei are of particular importance. Shock induced O burning produces mainly ^{40}Ca, ^{36}Ar, ^{32}S, and ^{28}Si in statistical equilibrium, while explosive Ne-burning mainly synthesizes ^{16}O,

^{24}Mg, and ^{28}Si. Explosive processes in O and Ne layers are also likely sites for the p-process, which is discussed in Section IX. Depending on the amount of C, He, and H fuel, the shock front can also induce explosive C, He, and H burning in the outer layers of the star. However, due to the low densities only minor modifications in the abundance distribution are expected.

For many of these reaction and structure needs, theoretical calculations will provide the bulk of the information; the experimental studies will be limited to the more important cases, and serve to validate and refine the theoretical approaches. Much progress has been made in the area of large-basis shell-model calculations, which will continue to expand the range of applicability of this more complete method. Quantum Monte Carlo methods allow the full fp-shell to be taken into account for the mass region A = 40-60. Such calculations provide detailed wave functions from which the masses of nuclei far from stability, Gamow-Teller strength functions for electron capture, beta-decay and neutrino interactions, spectroscopic factors, level densities and other quantities important for astrophysical calculations can be obtained. The fp-shell calculations have been used to calculate the electron-capture rates that play a central role in stellar collapse and supernova formation.

VIII. CATACLYSMIC BINARY STARS

Thermonuclear explosions in accreting binary star systems – novae, X-ray bursts and Type Ia supernovae – produce the most common explosive astrophysical events. At the conceptual level, the nature of the explosion mechanism seems reasonably well understood, but there are considerable discrepancies between the predicted observables and observations. An understanding of the time evolution of energy generation and nucleosynthesis, and of the nature of mixing and convective processes, is necessary to explain the observed luminosities and the abundance distribution in the ejected material. The proposed mechanism involves binary systems with one (or two) degenerate objects, such as white dwarfs or neutron stars, and is characterized by the revival of a dormant object via mass flow from the binary companion. The observed differences in the luminosity, time scale, and periodicity depend on the accretion rate and on the nature of the accreting object. These events involve nuclear processes at extreme temperatures and densities and synthesize a number of the important isotopes that make up our world.



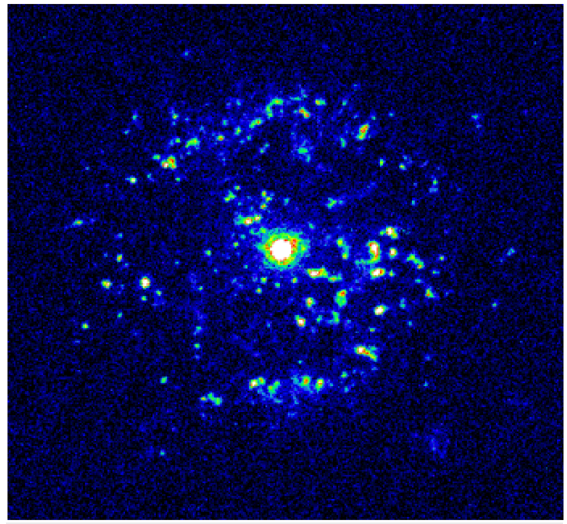
Artist's drawing of a nova before the nova explosion. Our Sun is unusual in that it is alone - most stars occur in binary systems. In a binary system, the higher mass star will evolve faster and will eventually become a compact object - either a white dwarf star, a neutron star, or a black hole. When the lower mass star later evolves into an expansion phase, it may be so close to the compact star that its outer atmosphere actually falls onto the compact star. Gas in this accretion disk heats up, and eventually falls onto the compact star. Steady or explosive burning of the accreted gas may occur leading to novae explosions, supernovae of Type Ia, X-ray bursters, or X-ray pulsars. In the case shown, gas is accreting onto a white-dwarf star.

Credit: S. Shore

Low accretion rates lead to a pileup of unburned hydrogen, and the ignition of hydrogen burning via pp-chains in an environment supported by electron degeneracy pressure. Once a critical mass layer is attained there are large enhancements in the rate of the reactions. On white dwarfs this triggers nova events, and on neutron stars it results in X-ray bursts. High accretion rates cause high temperatures in the accreted envelope and less degenerate conditions, and usually result in stable H-burning or only weak flashes. High accretion rates on white dwarfs may cause Type Ia supernovae (see Section VII); high accretion rates on neutron stars may explain X-ray pulsars.

Nova explosions

Novae are well described as thermonuclear runaways triggered by ignition of the slowly accreted hydrogen rich envelope via the pp-chains in degenerate electron conditions where the pressure is almost independent of temperature. This leads to a runaway situation in which the temperature rises and energy generation rates increase without expansion. During the thermonuclear runaway sufficient energy is released to raise the temperatures to 200 - 400 million kelvins before the degeneracy is lifted. The actual ignition temperature for novae is well below these peak temperatures. Rates of many nuclear reactions at energies below a few hundred keV are needed for a complete description of the ignition process in the various accreted layers of material. The main energy generation in novae, however, comes from the hot CNO cycle and is limited by the beta-decay rates of ^{14}O and ^{15}O. A theoretical description of the accompanying nucleosynthesis requires detailed knowledge of the rates of proton capture processes on short-lived radioactive nuclei in the CNO mass range. Detailed observations of the abundance distributions in nova ejecta confirm the general picture, but there are significant discrepancies that need to be addressed.



Hubble Space Telescope image of the recurrent nova T Pyxidis, 6,000 light-years away in the dim southern constellation Pyxis. The image reveals that the ejected material does not lie in smooth shells, but in more than 2,000 gaseous blobs or knots packed into an area that is 1 light-year across. The blobs may have been produced by the nova explosion, the subsequent expansion of gaseous debris, or collisions between fast-moving and slow-moving gas from several eruptions.

Credits: Mike Shara, Bob Williams, and David Zurek (Space Telescope Science Institute); Roberto Gilmozzi (European Southern Observatory); Dina Prialnik (Tel Aviv University); and NASA.

Elemental abundance variations found in "knots" of material ejected from nova explosions may be the key for understanding convective and mixing processes during the nova explosion. Observations of over-abundances in the Ne to S mass range, in the so-called Ne-novae, probably result from thermonuclear runaways on massive accreting O-Ne-Mg white dwarfs with mixing of oxygen, neon and magnesium into the accreting envelope. The nature of this mixing process is not understood. Extensive studies of proton induced nuclear reactions for both stable and radioactive nuclei in the Ne to Na and S to P mass ranges are necessary to understand this phenomenon.

Observations of the gamma radioactivity in novae, especially from the radioisotopes ^{22}Na and ^{26}Al, will continue to play an important role in constraining the Ne-nova models–the predicted intensity is larger than the observed limit on the intensity of the ^{22}Na gamma ray. Studies of the nuclear reactions involved in the synthesis of these radioisotopes, such as $^{21}Na(p,\gamma)$ and $^{22}Mg(p, \gamma)$, are therefore particularly important. It appears that peak temperatures in nova explosions may be much higher than (the currently accepted) 400 million kelvins. At such high temperatures, reactions can break out from the hot CNO cycle for some novae – there is evidence for breakout in one recent nova observation. Measurements of nuclear reactions on proton-rich unstable isotopes – including some above mass 40, the traditional endpoint of nova nucleosynthesis studies – are required to understand this higher-temperature nuclear burning.

X-ray bursts

X-ray bursts are thought to result from thermonuclear runaways in the hydrogen rich envelope of an accreting neutron star. Low accretion rates favor a sudden local ignition of the material with a subsequent rapid spread over the neutron star surface. Ignition of the triple-alpha reaction and breakout reactions from the hot CNO cycles trigger a thermonuclear runaway driven by the αp- and the rp-processes. The αp-process is a sequence of (α,p) and (p,γ) reactions that convert the ^{14}O and ^{18}Ne ashes of the hot CNO cycles to isotopes in the ^{34}Ar to ^{38}Ca range. The rp-process is a sequence of rapid proton captures leading to the proton drip line, followed by beta-decays of drip line nuclei that convert material from the Ar to Ca range into ^{56}Ni. The runaway freezes out in thermal equilibrium at peak temperatures of around 2.0 to 3.0 billion kelvins. Re-ignition takes place during the subsequent cooling phase of the explosion via the rp-process beyond ^{56}Ni. The nucleosynthesis in the cooling phase of the burst considerably alters the abundance distribution in the atmosphere, the ocean, and subsequently the crust of the neutron star. This may have a significant impact on the thermal structure of the neutron star surface and on the evolution of oscillations (waves) in the oceans.

Nuclear reaction and structure studies on the neutron deficient side of the valley of stability are essential for an understanding of these processes. Measurements of the breakout reactions will set stringent limits on the ignition conditions for the thermonuclear runaway; measurements of alpha and proton capture on neutron deficient radioactive nuclei below ^{56}Ni will set limits on the time scale for the runaway itself and on the hydrogen to seed ratio for the rp process beyond ^{56}Ni. Nuclear structure and nuclear reaction measurements near the double closed shell nucleus ^{56}Ni determine the conditions for the re-ignition of the burst in its cooling phase. Information beyond ^{56}Ni, especially in the Ge to Kr mass regions, is needed to determine the final fate of the neutron star crust. The nuclear structure information needed to calculate the flow of nuclear reactions in X-ray bursts and the time dependence of the energy generation, includes masses, beta-decay lifetimes (also needed for isomeric or thermally populated excited states), level positions, and proton separation energies, especially in the Ge to Kr mass region. The rates of two-proton capture reactions that may bridge the drip line at waiting points are of special importance.

X-ray pulsars

X-ray pulsars are usually described as accreting neutron stars with high accretion rates. This leads to steady burning of the accreted material via αp- and the rp-processes on the surface of the neutron star. Detailed studies of the nucleosynthesis suggest that the accreted material is rapidly converted to heavier elements in the mass 80 to 100 range. This drastically changes the composition of the crust and the ocean of the neutron star; the original iron crust is replaced by a mixture of significantly more massive elements. As a result, the composition of the neutron star crust in a binary system is substantially different from that in an isolated neutron star. This composition change may have important effects on the thermal and electromagnetic conditions at the neutron star surface, and will affect the observed decay of the magnetic field of neutron stars. It will also change the sequence of electron captures in the deeper crust, which may affect the emission of gravitational radiation from the neutron star surface.

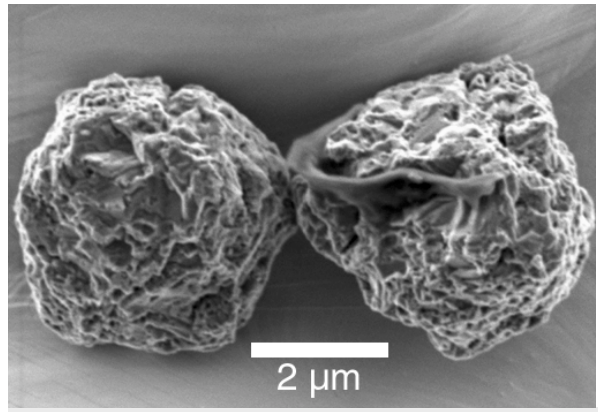
The final composition of the crust depends strongly on the nuclear physics associated with the rp-process and on the endpoint of the rp-process, which itself is directly correlated with the accretion rate. For experimental confirmation in the lower mass range, studies similar to those for the X-ray burst simulations are required. However, for large accretion rates the endpoint of the rp-process is expected to lie in the mass 150 range. This requires a new range of nuclear structure data near the limits of stability. Of particular interest are beta-decay lifetimes, and especially beta-delayed proton and beta-delayed alpha decays. If these processes dominate, as is expected for the decay of very neutron deficient tellurium, iodine, and xenon isotopes, one reaches a natural halting point for the rp-process.

Black hole and neutron star accretion disks

Many of the accretion processes on neutron stars and black holes are mediated by accretion disks. Nuclear processes that occur in this disk at low density and high temperature may alter the abundance distribution of the accreted material, affecting nucleosynthesis and energy release following ignition of the accreted material. One possible effect is spallation and fragmentation of the high velocity accreting material during its interaction with the outer atmosphere of the accreting object. Further theoretical study is needed to establish the importance of these phenomena.

IX. SYNTHESIS OF THE HEAVY ELEMENTS

Almost all nuclei heavier than iron are made by neutron capture on lighter seed nuclei in the s- and r- processes. A few rare isotopes are made by rather different mechanisms, known collectively as the p-process. The observed abundances of the elements and their isotopes in our solar system suggest that these processes take place at different characteristic time scales, temperatures, and neutron densities. Given nuclear physics input of sufficient breadth and accuracy, the synthesized abundances in this mass region provide a fertile field for developing and testing models of stars, stellar explosions, and more exotic phenomena such as the merger of two neutron stars.



Scanning electron microscope image of presolar silicon carbide grains from the Murchison meteorite. It is thought that these grains formed in the atmosphere of a red giant star, survived the formation of our solar system, and were transported to earth intact inside of this meteorite; hence, they preserve within them the signature of the environment in which they were created. The signature is the precisely measured relative abundances of isotopes of zirconium and molybdenum. Other grains or aggregates of grains contain other heavy elements. Their abundances can be compared to the signature calculated from various models for red giant stars. Precise neutron capture cross sections are required if such comparisons are to be used for improving stellar models.

(Photo courtesy of Andrew Davis, University of Chicago.)

The s-process

The solar-system abundances reveal that the s-process takes place under conditions where the time interval between neutron captures is longer than the average lifetime for beta-decay. As a result, the s-process proceeds through nuclides near the valley of stability and the resulting isotopic abundances are typically inversely proportional to the neutron capture reaction rates. The neutron capture rates on closed neutron shell isotopes are small, resulting in an enrichment of these isotopes and the characteristic s-process peaks in the solar-system abundance distribution. Models of the s-process also help to unravel the complex origin of the heavy nuclides–many of them are made by both the r- and s-processes. Because the s-process is better understood, the r-process abundances (the most important constraint on r-process models) are obtained from the measured solar abundances by subtracting the calculated s-process contributions. An important reaction in this regard is the neutron capture rate for ^{181}Hf (n, γ); this rate determines whether there is a significant s-process contribution to the abundance of ^{182}Hf, which is nominally an r-process nucleus. An accurate value of the r-process abundance of ^{182}Hf may help to determine whether there are two types of r-process (see Section III).

The observed s-process abundance distribution can be explained by two components, each with a different origin. The main component dominates nucleosynthesis in the region between Sr and Pb, and is associated with He-shell flashes in low mass (less than 4 M_{sun}) AGB stars (see Section VII). The weak s-process component is responsible for nucleosynthesis up to the A = 90 range and is thought to take place in massive stars (10-30 M_{sun}) during their He and C burning phases as discussed in Section VI. In addition to the synthesis of these heavier elements, the s-process is responsible for modifying the isotopic patterns of many lighter elements. The neutron sources are $^{13}C(\alpha, n)^{16}O$ and $^{22}Ne(\alpha, n)^{25}Mg$ for the main component and $^{22}Ne(\alpha, n)^{25}Mg$ for the weak component. Isotope production is directly proportional to the rates of these reactions. Unfortunately the rates have considerable uncertainties in the stellar energy region. Given the complexity of the nuclear structure involved, detailed measurements will be necessary to reduce these uncertainties.

Research on the s-process has undergone a renaissance in recent years, thanks to new more realistic stellar models, new extremely precise observational data, and improved experimental nuclear physics techniques and data. Until recently, even rather schematic s-process models reproduced the observed abundances rather well. However, as the precision of both the observations and the neutron capture cross section data has improved, it has become clear that more sophisticated models are needed. These new stellar s-process models are beginning to provide details about the inner workings of stars in which the s-process occurs and about related issues such as galactic chemical evolution. The lack of high quality neutron-capture data is now limiting further progress in these areas.

One example of precise new observational data is the discovery in certain meteorites of presolar grains. These grains of refractory material (e.g. SiC) apparently formed in a star in which the s-process was occurring, and found their way to the region of the galaxy in which our solar system was forming. Some of these grains survived the formation of our solar system, and were transported to earth intact inside meteorites; they preserve within themselves the signature of the environment in which they were created. This signature, relative abundances of isotopes of neodymium and other elements, can be compared to the abundances predicted by models for the s-process in AGB stars (see Section VI). Neutron capture cross sections accurate at the 1% level are required if these comparisons are to be useful for improving the stellar models.

One difference between the new stellar and older schematic models of the s- process is that neutron capture during the main phase of the s-process is now thought to take place at much lower temperatures (kT ~ 8 keV) than previously assumed (kT ~ 30 keV). This change in temperature requires extending many of the previous neutron capture cross section measurements to lower energies. Data of the requisite accuracy – 1% for stable nuclei – in this energy range can be obtained at electron linear accelerators or at spallation based white neutron sources.

An important opportunity is presented by the large neutron fluxes at present and planned spallation sources. These large fluxes make possible measurements of capture cross sections for radioactive nuclides that are branch points in the s-process. For these nuclides the neutron capture rate is comparable to the rate of radioactive decay. Data on these branch points can strongly constrain the neutron density and temperature of the s-process site.

The r-process
The r-process takes place in an environment of high temperature, exceeding 10^9 kelvins, and high neutron density, greater than $10^{20}/cm^3$, in an event lasting several seconds. In this circumstance the interval between neutron captures is much shorter than the lifetime for beta-decay. A rapid succession of neutron captures on a seed nucleus finally produces a nucleus with a neutron binding energy sufficiently small that the rate of capture is balanced by the rate of photodisintegration induced by the ambient blackbody photons. After some time at this waiting point, a beta-decay occurs and the capture process can begin again. As a result, nuclei tend to pile up at the waiting points. In this equilibrium approximation, the abundance of a nucleus is proportional to its half-life. A special case, where pile-up is large, occurs near neutron shell closures, because beta-decay lifetimes are long and because waiting points recur after only a single neutron capture. At the end of the r-process event, the radioactive products decay back toward the valley of stability, sometimes emitting neutrons in the process. The resulting abundance peaks, occurring on the low-mass side of the s-process peaks, are the signature of the r-process.

At present the astrophysical site of the r-process is under debate. The hot neutrino-heated bubble outside the protoneutron-star in a supernova is in many ways an ideal site. Since r-process abundances appear to be independent of the preexisting heavy-element enrichment of the star (Section IV) the r-process site must produce its own seeds – the hot-bubble site seems to do so. However, some models suggest that the entropy in this bubble is too small to reproduce the observed abundance distribution. Consideration of general relativistic effects may resolve this problem. Or, it may be necessary to consider other sites such as merging neutron stars.

Despite these uncertainties, the general features of the r-process outlined above determine what nuclear information is required. The path of r-process flow is through neutron-rich nuclei, far from the valley of stability. It passes through nuclei with neutron binding energies of about 1-4 MeV, depending upon parameters such as neutron flux and temperature. For nuclei on the r-process path one needs to know masses with an accuracy of 100 keV or better, beta-decay lifetimes, and the number of neutrons that are emitted in the beta-decay chain leading back to the valley of stability. When the reactions freeze out as the temperature and neutron density decline near the end of the event, it may become necessary to know some radiative neutron capture cross sections. Even at spallation neutron sources, neutron capture measurements will be possible only for radioisotopes near the valley of stability. These data may serve to calibrate nuclear models for calculation of reaction rates for more neutron-rich nuclides. Measurements of Coulomb-breakup – the inverse of the (n, γ) reaction – and of (d, p) with radioactive beams can also provide information on these cross sections.

Mass measurements can be made, for example, using Penning traps, by comparing time of flight and magnetic rigidity, either in storage rings or with spectrographs, or by measuring beta-decay endpoints in coincidence with the associated gamma rays. Observation of the gamma rays also provides the information on nuclear excited states that is necessary to calculate partition functions as well as corrections to beta-decay rates and capture cross sections. The technique of choice will depend on the lifetimes and achievable beam intensities. Both ISOL and fragmentation facilities will be needed for these measurements.

Lifetime measurements are possible with very small intensities, perhaps a few per hour, and can be carried out by a variety of production techniques that can provide isotopically clean beams: for example by standard ΔE-E time-of-flight techniques, very-high-resolution mass separators, or chemically selective laser ion sources. Near the production limits, fragmentation facilities that can work with beams of a few per hour will probably be most effective.

Even the next generation radioactive beam facilities will not allow one to study all of the nuclei on the r-process path; some theoretical extrapolations will still be necessary. Making them more reliable will require systematic studies of neutron-rich nuclei far from the beta-stability line. Properties of interest include energies of single-particle states and associated shell structures, spectroscopic factors, nuclear deformations, level densities, and beta-strength distributions. These studies have begun for nuclei near doubly magic ^{132}Sn and for neutron-rich lighter nuclei. Both ISOL and fragmentation facilities will be needed to obtain the required information.

A particularly striking feature of some theoretical calculations is the prediction that the strength of shell closures decreases – i.e. the gaps between single particle energy levels diminish – as neutron-rich nuclei become less bound near the neutron drip line. Weaker shell gaps affect mass and half-life predictions, which in r-process models results in a filling of the valleys below the main r-process peaks and a better description of the abundances. This apparently supports the theoretical conclusion and indicates that the r-process is sensitive to decreased shell gaps. However, it is difficult to know whether other processes might produce similar effects, especially since the site for the r-process is still uncertain. Nuclear properties should be based on nuclear physics measurements, if at all possible, rather than inferred from complex astrophysical phenomena – else the arguments for an accurate description of the r-process become somewhat circular.

There is evidence that the intense neutrino flux present in a supernova site can remove nucleons from r-process peak nuclei, thereby producing some rare and previously under-produced nuclei. If this process could be calculated precisely – which requires accurate values of the breakup cross sections – it could help to determine the number of neutrinos passing through the site, and the endpoint of the r-process.

The p-process nuclei

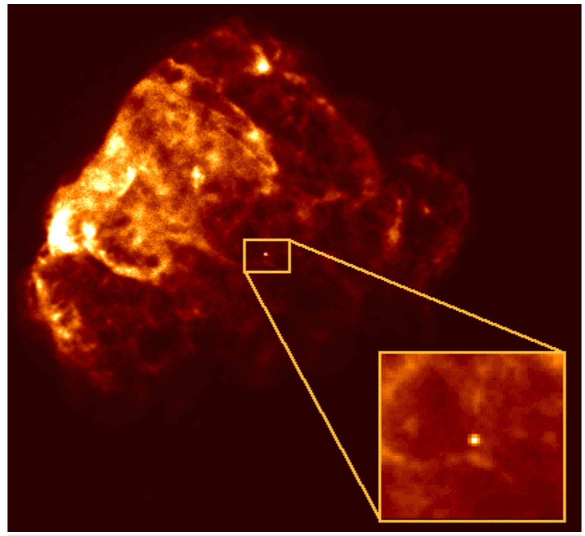
The r- or s-processes cannot make certain rare nuclides that lie on the proton rich side of the valley of stability. Understanding the synthesis of these p-process nuclei has been a long-standing challenge, partly because at least three different processes can produce them: the gamma-process, the rp-process, and the neutrino-process. The gamma-process is the result of a high temperature stellar environment, such as that found in supernovae, and involves photo-erosion of preexisting abundant heavy nuclides by (γ, n), (γ, p), and (γ, α) reactions induced by the ambient blackbody photons. The nuclear statistical model should be applicable for the calculation of the rates of these reactions. Comparison with (n, γ) and (p, γ) data show that these rates (and their inverses) can often be predicted to within a factor of two. In contrast, (α, γ) measurements indicate that the calculated rates can be wrong by a factor of ten or more, apparently because of poorly known alpha-particle optical potentials at such low energies. These uncertainties might be reduced substantially by low-energy (n, α) measurements that can constrain the alpha potentials. Studies of Coulomb-breakup of radioactive nuclei at a fragmentation facility or using a free electron laser facility should also provide information on these reactions.

The rp-process that occurs in the hydrogen-rich layer accreted on a neutron star may be responsible for production of some of the lighter p-process nuclides: isotopes of Mo and Ru, whose anomalously high abundances have been difficult to produce in the gamma-process models. The rp-process is discussed in detail in Section VIII. An additional issue is whether the radiation pressure is sufficient to overcome the enormous gravitational attraction of the neutron star and blow a small fraction of the produced material into the interstellar medium. This depends on the rate of energy production. To determine the feasibility of the rp-process will require measurements of masses and beta-decay lifetimes for the progenitors of Mo and Ru (light Pd, Ag, and Cd isotopes), and around lower-mass bottlenecks such as ^{72}Kr.

The neutrino-process occurs in the high neutrino flux produced by the protoneutron-star in a core-collapse supernovae (see Section VII). More abundant nuclei are excited to unbound states (which later undergo particle decay) by neutrino induced inelastic scattering or charge exchange reactions. This mechanism can affect the abundances of r-process nuclei, especially those on the lower-mass side of the r-process peaks, and produce a significant abundance of rare isotopes like ^{7}Li, ^{11}B, ^{19}F, ^{138}La, and ^{180}Ta. It may also produce light p-process nuclei such as ^{92}Mo. The cross sections for the relevant neutrino-induced reactions can be inferred from studies of inelastic hadron scattering and charge exchange at energies of 100-200 MeV/nucleon. Such experiments can be done for stable or radioactive isotopes at fragmentation facilities. Measurements of neutrino-induced reactions on ^{12}C and ^{56}Fe have been performed at LSND and KARMEN, showing that such studies are feasible. In the future, better measurements may be possible at new spallation neutron sources.

X. NEUTRON STARS

At the end of the life of a massive star, its iron-like core collapses and the resulting supernova explosion disperses the outer part of the star into the interstellar medium. In most cases the explosion leaves behind a part of the core, an extraordinarily dense object, a neutron star with a typical mass 1.5 times that of the sun and a radius of about 10 km. Intense gravitational forces compress the star, which at its center has a density 10^{15} times that of water.



An X-ray image of the Puppis A supernova remnant, created using data from the ROSAT High Resolution Imager. Puppis A is the supernova remnant of one of the brightest sources in the X-ray sky, with shocked gas clouds still expanding and radiating X-rays. In the inset close-up view, a faint pinpoint source of X-rays is visible which is most likely the young neutron star, kicked out by the asymmetric explosion and moving away from the site of the original supernova at about 600 miles per second. Directly viewing a neutron star is difficult because it is small (roughly 10 miles in diameter) and therefore dim, but this newly formed neutron star is intensely hot, glowing in X-rays.

Credit: S. Snowden, R. Petre (LHEA/GSFC), C. Becker (MIT) et al., ROSAT Project, NASA.

As one descends from a neutrons star's surface toward its center one passes through an iron-like solid crust; a region where energetic electrons are captured by nuclei whose ratio of neutrons to protons thereby increases; into regions where nuclei may have linear or sheet-like shapes; then after about one kilometer into a region containing a nuclear fluid mostly composed of neutrons and trace amounts of protons and electrons; and finally at higher densities into a more or less unknown region near the stellar center, which may contain muons, heavy relatives of electrons, pions, kaons, lambda or sigma baryons, or even quark matter or quark-matter droplets. It appears that large parts of a neutron star could exist in a mixed phase, for example, a mixture of ordinary hadronic matter and quark matter.

The experimental and theoretical exploration of the structure of neutron-star matter and the determination of the equation of state (EOS) associated with such high-density matter is of key importance for understanding the physics of neutron stars and supernova explosions.

Direct observational evidence about the structure of neutron stars has been limited to their masses, rotation rates, and occasional glitches in the regular rotations of pulsars. Indirect techniques involving quasi-periodic oscillations in binary neutron star systems provide weak limits on neutron star masses and radii. Now it appears that one may be able to measure directly the radii and surface temperatures in selected cases, and when LIGO is operational, to observe the gravitational wave signature of the merger of two neutron stars. The observations will be sensitive to the equation of state of neutron-star matter, while the surface temperature will also provide a measure of the cooling rate of the star by emission of neutrinos. This cooling depends as well on the possible presence of particles other than neutrons, protons, muons, and electrons in the stellar core. In total, these developments make understanding of dense neutron-rich matter an urgent issue.

Since the properties of a neutron star depend on the nuclear equation of state, and hence on the compressibility and symmetry energy of nuclear matter, it is important to determine these quantities. The compressibility can be obtained from the frequencies and strengths of nuclear vibrations that involve the compression of nuclear material, the isoscalar monopole and isoscalar dipole resonances. Observation of these resonances with considerably improved sensitivity is important, and should be supplemented by a search for weak components of their strength that might change the average vibration frequency. On the theoretical front, calculations should be carried out to develop interactions that reproduce the resonance data. The apparent 30-40% discrepancy between the compressibilities deduced from the isoscalar-monopole and isoscalar-dipole resonances needs to be addressed both experimentally and theoretically.

The bulk symmetry energy of nuclear matter describes the dependence of the energy on the relative number of neutron and protons; it reflects the difference in the nuclear interaction between two neutrons or two protons, and the stronger interaction between a neutron and a proton. The symmetry energy is of great importance for studies of neutron stars, nucleosynthesis, and supernovae. It affects the collapse of massive stars, neutrino emission rates, the cooling rates of protoneutron-stars, and the predicted correlation between the radius of a neutron star and the pressure of neutron-star matter near normal nuclear densities. Both the magnitude and the density dependence of the symmetry energy are poorly known. Since the surface symmetry energy of nuclei (dependent on their radius) is related to the density dependence of the bulk symmetry energy, measurements that can distinguish between the volume and surface symmetry energies in nuclei are particularly valuable.

Experimental information on the symmetry energy could be obtained from: (1) Determination of the masses of heavy neutron rich nuclei far from the valley of stability; (2) Positions and strength distributions of isovector resonances; and (3) Observation of the collective flow of matter, momentum, and energy in collisions of neutron rich systems at energies of roughly 100-500 MeV/nucleon, with the N/Z ratio adjusted using radioactive beams.

The equation of state of high-density matter is being studied theoretically with three distinct approaches: Schrödinger-based treatments using on two- and three-nucleon interactions, effective field-theoretical approaches, and relativistic Dirac-Brueckner approaches. While all of these approaches yield satisfactory results for normal nuclear density, considerable differences persist in their medium and high-density behaviors, largely because of the poorly constrained many-body interactions. These uncertainties manifest themselves in significant uncertainties in the predicted radius (7-15 km), maximum mass (1.5-2.5 M_{sun}), and maximum rotation rate of a neutron star. Several theoretical approaches (automated algebra techniques, Monte Carlo techniques in a potential model approach, and field-theoretical methods in which the uncertain four-body interaction could be calibrated by measurements of neutron star radii) may make it possible to better constrain the high-density behavior. There is renewed interest in performing better many-body calculations to explore the possibility of charged pion or kaon condensates in neutron star matter.

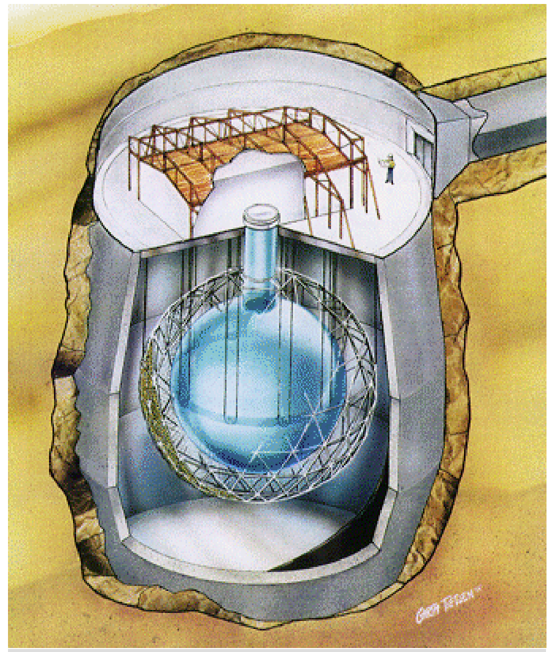
Relative to nucleons-only matter, neutron star properties may be significantly affected by the presence of other particles (hyperons, deltas), or novel states of matter such as pion or kaon condensates, or deconfined quark matter. The latter, being sought at heavy ion colliders, could lead to metastable neutron stars that subsequently end their lives as black holes, or could manifest itself in a hysteresis in the spin-down rate of rotating neutron stars (pulsars). Such stars could anomalously spin up for about 10^6 years before resuming a normal spin-down.

Another possibility is that hadronic and quark matter exist in a mixed phase. Quark matter could first appear as small droplets, which grow and gradually become the dominant matter at higher densities deep within the star. The resulting inhomogeneities in the matter could have dramatic effects on the cooling properties of neutron stars. There is a strong connection between these phenomena and experiments at heavy ion colliders. If these experiments determine the conditions for deconfinement, and bulk properties such as the surface tension between confined and deconfined phases, better models of neutron stars should follow.

The resistance to the neutrino flow, or neutrino opacity, for neutrinos in dense nuclear matter has major consequences for the behavior of neutron stars. At high densities the typical momentum transferred in scattering processes is larger than the internucleon (or interquark) separation. To predict the opacity in these conditions, one must determine the collective response of the matter: screening, inhomogeneities, and fluctuations all play a role in determining density and spin-related correlations. Neutrinos might then serve as probes of the properties of very dense, neutron-rich hadronic matter. An elevated opacity, perhaps caused by quark matter droplets, might lead to an extended tail in the cooling curve of the protoneutron-star formed in a supernova. It is a theoretical challenge to make this connection quantitative, and an experimental challenge to measure precisely the neutrino flux from the next galactic supernova.

XI. NEUTRINOS IN ASTROPHYSICS

More than 60 years after the neutrino was proposed by Pauli as a way to preserve conservation of energy and angular momentum in beta-decay, its nature remains enigmatic. Nevertheless, neutrinos play a fundamental role in the evolution of the universe, in the creation of the elements in the big bang and in supernovae, and as a potential signature of new physics beyond the Standard Model of nuclear and particle physics.



The SNO detector, shown in the artist's conception above, was built 2100 meters below ground, in INCO's Creighton mine near Sudbury, Ontario. SNO uses 1000 tons of heavy water, contained in a 12m diameter acrylic vessel shown in blue at the center of the figure. Neutrinos react with the heavy water (D_2O) to produce flashes of light called Cerenkov radiation. This light is then detected with a geodesic array of 9600 light detectors (photomultiplier tubes) surrounding the heavy water vessel. Location in the deepest part of the mine provides a large overburden of rock to shield from cosmic rays. The detector laboratory is kept exceptionally clean to reduce background radiation signals which would otherwise hide the very weak signal from neutrinos. The detector is operating and has seen events produced by neutrinos.

Nuclear physics and astrophysics are central to our efforts to understand the neutrino. The first hints of neutrino mass emerged from the neutrino fluxes obtained from solar neutrino experiments. Double beta-decay is our best test of the charge conjugation properties of neutrinos, distinguishing Majorana from Dirac masses. Tritium beta-decay provides our most stringent bound on kinematical masses. Finally, nucleosynthesis in the big bang and within supernovae provides powerful constraints on the number of neutrino generations and mixing. Neutrino physics is a bridge connecting nuclear physics, particle physics, and astrophysics. Astronomical sources of neutrinos may present the best opportunities to understand the fundamental properties of neutrinos and neutrinos may be the most fundamental source of information about the interior properties of stars.

Solar neutrinos and neutrino oscillations

The last decade has seen major advances in neutrino physics and in our understanding of the importance of neutrinos in astrophysics. It appears that neutrinos can oscillate or change from one type (flavor) to another, implying that different neutrinos have different masses. These properties are not included in the simplest Standard Model of particle and nuclear physics. Strong indications of oscillations came first from solar-neutrino experiments with the chlorine detector. The deficit of detected electron neutrinos could be explained if some of them oscillated into muon neutrinos on the way to the chlorine detector. Since it was not sensitive to muon neutrinos, these oscillations could resolve the solar neutrino problem. Related evidence came later from the Liquid Scintillator Neutrino Detector (LSND) at Los Alamos. In 1998, the SuperKamiokande collaboration reported evidence for oscillations of neutrinos resulting from the decay of pions and muons in the atmosphere. Recent theoretical advances show that passage of neutrinos through the matter of the sun or the Earth on their way to a terrestrial detector could enhance the effects of neutrino oscillation in an energy dependent way (MSW mechanism) and that neutrinos could affect the explosive nucleosynthesis that occurs within supernovae.

A straightforward picture of oscillations among the three known neutrino flavors, the electron, muon and tau neutrinos cannot explain the available data: there are only two mass differences between three neutrinos and the experiments, if all are correct, require three differences. Scenarios that include sterile neutrinos, neutrinos that have no interactions with other particles, can accommodate all experiments. For the first time, we have a road map of where to look in neutrino physics to explain the data. Much of the needed exploration involves the study of astrophysical sources of neutrinos. The coming decade will be an exciting time, as the long-standing mysteries surrounding the neutrino begin to fall one by one. The resolution of these uncertainties will have a strong impact on our understanding of astrophysical phenomena.

A set of complementary solar neutrino experiments (Chlorine, Kamiokande, SuperKamiokande, SAGE, and GALLEX) has yielded a powerful result. Chlorine, Kamiokande and SuperKamiokande are sensitive mainly to high-energy neutrinos from the decay of ^{8}B produced in the sun, and SAGE and GALLEX mainly to neutrinos from the decay of ^{7}Be and the low energy neutrinos from the fusion of two protons. Yet no combination of undistorted solar neutrino fluxes can reproduce all the experimental rates. Neutrino oscillations can account for the data, although a single, consistent solution has not yet emerged. The strong possibility of matter enhancements has enriched the experimental possibilities: observable distortions of the neutrino energy spectrum, day-night effects, and yearly variations can all occur. An experiment just beginning at the Sudbury Neutrino Observatory (SNO) can detect muon or tau neutrinos with high efficiency and distinguish them from electron neutrinos. Whether SNO confirms neutrino oscillations by direct measurement of an enhanced neutral current rate (tau or muon neutrinos), or shows that the oscillation phenomenon likely involves sterile neutrinos, more precise and powerful detectors will be needed to define the physics. The challenge of building detectors to measure the spectrum and flavor of pp and ^{7}Be neutrinos is still largely unmet. The Borexino liquid-scintillator detector will provide the first spectral information on ^{7}Be. New developments that could provide the means for studying low energy neutrinos are of great interest for a next generation detector.

The supernova mechanism and supernova neutrinos

Supernova explosions (see Section VII) present a unique opportunity to use neutrinos to probe fundamental and interrelated issues: the mechanism driving the supernova, the masses and mixings of neutrinos, and the synthesis of new nuclei within our galaxy. The goal is similar to the initial goal of solar neutrino detection, to probe nuclear processes otherwise hidden in stellar cores.

The supernova mechanism is one of the important "grand challenge" problems in computational physics. Resolving the puzzle will have far-reaching implications for astrophysics and will help define the neutrino signature of supernova neutrino mixing. As so much of the underlying physics – neutrino diffusion, the core bounce, weak interaction rates, and explosive nucleosynthesis – is nuclear in origin, nuclear astrophysicists are leading the efforts to understand the supernova mechanism. The great current excitement in this field is driven by the near-term prospect of massively parallel calculations in which 2- and 3-D modeling with full Boltzmann transport becomes possible for the first time, by the promise of reliable nuclear data as input for these calculations, and by the possibility of detecting the neutrinos emitted by the next supernova.

The resulting improved understanding of the supernova mechanism will make the explosion a more powerful "laboratory" for astrophysics and particle physics. Neutrinos directly influence supernova nucleosynthesis, controlling the neutron-proton balance responsible for the r-process and synthesizing some light and heavy nuclei by neutrino induced breakup. Future radioactive beam experiments will determine the nuclear structure properties which affect the r-process and supernova neutrino flux measurements will similarly constrain the astrophysical setting in which this synthesis takes place. These complementary constraints will allow great progress.

An understanding of the time structure of the neutrino burst – its rise time, the possibility of a pulse of very short duration, and its long time evolution – is crucial to future kinematic tests of neutrino masses by time-of-flight delays. A delayed collapse into a black hole could well lead to a sudden turnoff of the neutrino burst. Another important issue is the nature of oscillations from electron to tau neutrinos, a potentially fascinating probe of cosmologically interesting tau-neutrino masses: even modest mixing strength could produce large effects on the supernova neutrino flux. Model-independent arguments show that the temperature characterizing muon and tau neutrino sources is about twice that of electron neutrinos. As a result, an electron neutrino to tau-neutrino oscillation leads to a distinctive temperature and neutrino energy inversion that can have a distinctive signature in terrestrial detectors.

Supernova neutrino detection will also make an important contribution to conventional astronomy. The neutrinos leave the core hours before the electromagnetic radiation leaves the envelope and could give an early warning of a galactic supernova. It may also be possible to determine the supernova direction to within about five degrees by using the forward-peaked neutrino-electron scattering signal. This would allow astronomical observations from the earliest possible time.

Facilities for neutrino physics

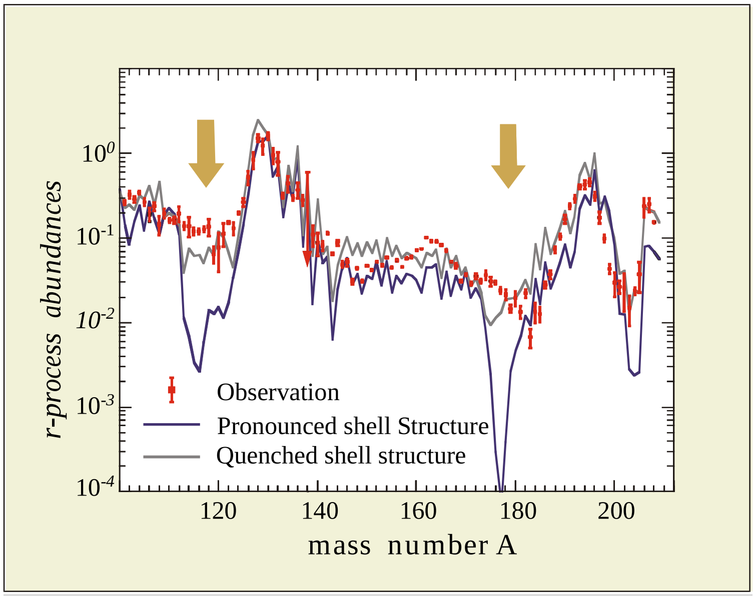
The importance of the issues addressed by neutrinos from supernovae warrants a strong effort to assure that neutrinos from the next galactic supernova will be detected with good statistics. If SNO and SuperKamiokande are operating at the time of the next supernovae, they will yield thousands of events for a supernova similar to SN1987A. However, it is necessary to obtain the time structure and energy distributions for separate flavors – for these purposes new types of detector are needed. These detectors must be operated as observatories, since galactic supernovae occur only about once every 30 years. Proposals are being developed, for example, for detectors of neutrino induced breakup reactions involving lead or iron, and for a one-kiloton iodine detector. Other ideas should emerge as the field grapples with the task of continually monitoring the galactic neutrino flux, in concert with other types of astrophysical observatories.

Beam-stop neutrinos and reactor antineutrinos are mainstays of research into neutrino properties because of their intense fluxes and moderate energies. The LSND result is of fundamental importance in cosmology. It appears to define a lower limit to the mass contribution of hot dark matter at a level that would significantly affect the large-scale structure of galaxy clusters and superclusters. For this reason, new experiments are essential. The new Spallation Neutron Source could greatly improve the search for oscillations under conditions in which LSND finds a signal. In addition, the intense radioactivity of the beam stop might serve as a neutrino source.

Low energy and intermediate energy accelerators are important in this phase of development of neutrino physics. Measurements of the (p, n*)* and (^{3}He,t) reaction at energies of 100-200 MeV/nucleon are often the most practical technique available for estimating neutrino cross sections important to supernova or solar neutrino detection. The connections between r-process nucleosynthesis and supernova neutrino oscillations promise to illuminate both processes. Measurements of masses and beta-decay rates at future radioactive beam facilities are our best hope of making these connections quantitative. Finally, given the subtle distortions now being sought in SNO and SuperKamiokande, the energy spectrum and intensity of solar neutrinos must be better defined if one is to obtain reliable information from solar neutrino detectors. This will involve experiments on pp-chain and CNO-cycle reactions, e.g. ^{3}He(α, γ)^{7}Be, ^{7}Be(p, γ)^{8}B, and ^{14}N(p, γ)^{15}O, and on the shape of the beta-decay spectrum of ^{8}B. Theory will also play an important role: "exact" few-body techniques will likely provide the best constraints on the intensity of the highest energy neutrinos from the sun, those from the poorly understood $^3\text{He}+\text{p} \rightarrow {}^4\text{He} + e^+ + \nu$ reaction.

XII. NUCLEAR STRUCTURE AND DATA IN NUCLEAR ASTROPHYSICS

Nuclear structure and nuclear astrophysics are intricately connected. Energy generation in stars, nucleosynthesis, stellar explosions, neutron stars, and neutrino interactions are all affected by nuclear properties. The distinction between research in nuclear physics and nuclear astrophysics is often only in the specific application of the results.



Observed abundances of r-process nuclei compared to two predictions of these abundances from r-process network calculations. The calculations are based on two different spherical models of nuclear structure. In one of these (labeled "pronounced shell structure") the nuclear shell structure is similar to that of stable nuclei. In the other (labeled "quenched shell structure") the shell gaps are reduced as predicted by some structure calculations. At the nuclear masses noted by the orange arrows, the quenched calculations better describe the observed abundances: the r-process abundances are sensitive to details of nuclear structure.

Adapted from B. Pfeiffer, *et al.*, Z. Physik **A357**, 253 (1997)

Data requirements

Nuclear quantities of interest can be grouped roughly into three categories: global nuclear properties (masses, lifetimes, nuclear matter), properties of excited states (isomers, level densities, electroweak strengths, decay rates), and reaction aspects (cross sections, resonance structure, interference properties). Each of these properties has a direct impact on astrophysical processes and on the observable signatures they leave behind. Measured and compiled values are usually limited to nuclei that are close to the valley of stability. Many nuclear properties that are important for the understanding of astrophysical processes have not been measured, and some may never be accessible in the laboratory – nuclear theory will play a central role in providing this information.

Although many astrophysically important neutron-rich nuclei may not be experimentally accessible, they are important for nucleosynthesis in cataclysmic events such as supernovae. Consequently, new insights into nuclear structure in this terra incognita can sometimes be offered by astrophysical data. For instance, the analysis of the r-process abundances provides an indirect hint that shell splittings may be smaller for large neutron excess. Such hints provide an impetus to confirm or refute this assumption more directly by studies in nuclear physics.

Theoretical approaches, progress and directions

Nuclear theorists attempt to correlate known data by practical models and to predict the behavior of nuclear systems in new regimes. Theory plays an important role in the analysis of experiments, and in suggesting what new data would be valuable in future work.

Microscopic nuclear models continue to improve due to advances in theoretical techniques and computational resources and to improvements in the data that are used to constrain the input parameters. Exact theoretical solutions are still not possible for most nuclei, but one can obtain essentially exact solutions for systems containing up to eight nucleons, and very good results for infinite nuclear matter. The precise data on nucleon-nucleon scattering are used as input, and three-body interactions are also important. Most of the reaction rates for big-bang nucleosynthesis and solar neutrino production can be addressed by these ab initio calculations. Faddeev and hyperspherical harmonic methods give exact 3- and 4-body scattering solutions today, and Green's function Monte Carlo methods are promising for larger nuclei, up to at least A = 12. Since most low-energy reactions occur at large radii, further work is needed to incorporate appropriate asymptotic forms for the bound and continuum wave functions. These exact methods are also important for understanding the validity and limitations of the more approximate many-body techniques that must be used for heavier nuclei.

For the entire range of larger nuclei one relies upon mean field and shell-model configuration mixing methods. Both of these methods have recently been refined and improved. Of the mean field models, the energy-density functional methods have been most successful. For example, in the Skyrme-Hartree-Fock method the nuclear properties are related to a few (6-12) parameters of a density-dependent interaction that are determined by fitting nuclear data. This method, together with quasiparticle RPA calculations of the Gamow-Teller strength functions, provides an initial assessment of the global mass, beta-decay, and electron capture properties that are needed to describe supernova-core collapse, the r-process, and rp-process. The beta-decay half-lives are determined by the small part of the Gamow-Teller resonance that lies at low excitation energy. This aspect of the calculations needs to be improved. Hartree-Fock might be most appropriate for spherical and deformed regions, but for intermediate regions, the generator coordinate method or its equivalent should be used.

Large-basis shell-model calculations provide a more complete picture, in principle, but have been limited by the large dimensions of the valence spaces encountered in typical astrophysics applications. However, the newly developed quantum Monte Carlo and quantum Monte Carlo diagonalization methods, and a greatly improved direct diagonalization approach, have greatly expanded the range of shell-model applications. It is now possible to take the full fp-shell basis into account for the mass region A = 40-60. These calculations require, as input, interactions (G matrices) for extremely large model spaces. They are obtained from modern nucleon-nucleon potentials, with appropriate (e.g. monopole term) corrections. Ultimately, they will be obtained in a model-independent way by fitting to observed energy levels. The direct diagonalization approach provides detailed wave functions from which one can obtain information important for astrophysics: the masses of nuclei far from stability, Gamow-Teller strength functions, spectroscopic factors, and level densities. For example, the fp-shell calculations have provided the weak interaction rates that are needed to understand stellar-core collapse and supernova formation. Monte Carlo methods have been used in the sdg-shell for nuclei in the ^{100}Sn region. One can expect much more progress in this direction in the future.

For light nuclei one can consider "no-core" model spaces that take into account up to about 10 harmonic-oscillator shells. The interactions for these calculations are obtained from nucleon-nucleon scattering G-matrix elements, and improved methods, using the Bloch-Horowitz method to describe effective many-body interactions, are now being explored. The shell-model codes OXBASH and ANTOINE are available for use by researchers, and other more powerful codes are being developed.

Challenges for nuclear theory from the astrophysics viewpoint

- To determine the cross sections for important reactions in few-body systems. Could the $^{3}He + p \rightarrow {}^{4}He + \nu_e + e^+$ cross section possibly be large enough (over 10 times the present estimate) to explain the high-energy flux in Super-Kamiokande?

- To develop a continuum shell-model method to deal with the contributions of unbound orbitals as one nears the neutron drip line. Are the shell splittings reduced (quenched) for n-rich nuclei? Can one find signatures of this quenching in the observable regions, thereby giving guidance to experimental studies?

- To determine the weak interaction response of nuclei for both neutron and proton rich nuclei. Perform detailed large basis shell model calculations to provide the electron capture and beta-decay strengths necessary to simulate the evolution of the supernova core and the r-process. Obtain the global neutrino interaction rates for both charged and neutral-currents necessary to assess the role of neutrino induced reactions and energy transfer in supernovae – transitions to unstable states should be included.

- To obtain appropriate asymptotic forms of many-body wave functions for reaction calculations and their comparison with experimental results.

- To develop a reliable temperature, density, N/Z dependent equation of state appropriate for use in various astrophysical sites, including neutron stars and supernovae.

Application to nuclear astrophysics

The interaction of nuclear theory with astrophysical theory is complicated. In the context of nuclear physics, when a nuclear structure calculation has been completed it is compared with experiment, and if necessary revisited taking the experimental results into account. In the context of nuclear astrophysics several additional steps are necessary. Since information on a broad range of nuclei is often required, development of an extrapolation or interpolation procedure may be necessary if the theoretical calculations are difficult or time consuming. The theory must then be validated by comparison to an appropriate range of experimental data. If its predictions are not as accurate as is required, the theory must be “normalized” to experiment in an appropriate fashion. Then, relevant cross sections or lifetimes must be calculated. This may involve straightforward computations of matrix elements or strengths. Or it may, for example, involve computations of inelastic neutrino scattering cross sections, or of radiative capture cross sections for isolated resonances, or the use of statistical approaches. Finally, these results must be expressed in terms of temperature dependent astrophysical rates.

The complexity of the above task means that considerable thought must be given to deciding when a new theory is sufficiently developed and sufficiently different from its predecessors to warrant revising the reaction rates. It also means that a coordinated effort must be made to address these problems – the theoretical strength at any single institution will be insufficient. Perhaps such a coordinated effort could help to ensure that the structure of the rate calculations and of the astrophysics programs that use them is such that improved theoretical and experimental information can be incorporated with relative ease.

An important role of theory in nuclear astrophysics lies in providing guidance on the required measurements. Many astrophysical processes involve networks of reactions and decays; often it is far from clear whether a change in a particular nuclear property will have an impact in the astrophysical scenario. At other times, reactions occur under conditions of thermal equilibrium, and only the masses of nuclei and beta-decay strength are important. The importance of a given reaction may depend on the specific situation, for example on the mass of the star involved. Finally, it is clear that this process must be iterated, since changes in some rates may affect the importance of others. It will not be simple to provide guidance on the precision with which a given rate must be known, but it is essential to provide this guidance so that our experimental and theoretical efforts can proceed efficiently.

A related issue is the need to ensure that the available data are quickly and conveniently accessible to those involved in using them directly for the generation of rates for astrophysical models, or as part of the evaluation process for theoretical calculations. Else much of the effort involved in making these difficult measurements will be wasted.

XIII. REQUIRED ACCELERATORS

Experimental nuclear astrophysics is often viewed as involving long experiments using small accelerators to measure cross sections at lower and lower energies, and then finding a way to extrapolate still further to the energies relevant to stellar environments. While this certainly describes the "classical" approach for determination of reaction rates, this view was never fully correct; in some important cases, such as the triple alpha process, rates were based on indirect structure measurements. Low energy studies will remain important, and will typically take place at the limits of detectability for the reaction products. Dedicated sources of low energy, high intensity (10^{16}/sec range) beams with extraordinary stability and energy accuracy are required. Passive or active techniques for reduction of natural and beam-induced radiation background will often be important. For some problems, underground facilities or inverse kinematic techniques with intense heavy ion beams may be used to optimize signal to background ratios.

Information equivalent to that from the direct measurement of cross sections can often be obtained from measurements of the properties of nuclear states. These indirect approaches will be important in the future. Partly this is because some astrophysical cross sections are so small that direct measurements are impossibly prolonged. Partly it is because indirect measurements provide a more efficient way of obtaining information that could in principle be determined directly. And partly, in particularly difficult or important cases, the different systematic errors associated with direct and indirect approaches may provide a better estimate of the total uncertainties and thereby, a more useful result.

A broad range of complementary approaches and facilities is required to address the many challenges described in this report. In addition to the low energy stable-beam facilities mentioned above, these approaches include (1) Radioactive ion beams that cover the range of nuclei produced in the cosmos with energies from about 100 keV/nucleon to hundreds of MeV/nucleon. Intensities will vary widely, but it will be desirable to perform certain experiments on nuclei approaching the limits of stability, with beams of 1-100 ions/day. (2) Stable beams with high energy, from a few MeV/nucleon to several GeV/nucleon and moderate intensity. (3) Spallation neutron sources and electron linacs for neutron and neutrino-induced reactions. (4) Free-electron lasers, for studies with high-energy gamma rays.

To illustrate these approaches, we will use as examples two reactions that have been studied by a variety of approaches: the $^{12}C + ^{4}He \rightarrow ^{16}O + \gamma$ and the $^{7}Be + p \rightarrow ^{8}B + \gamma$ reactions. The first of these reactions is important in determining whether the ashes of helium burning stars are dominantly carbon or oxygen, and the second determines the flux of high energy neutrinos emitted by the sun. The earliest studies of these reactions used the classical method: low energy alpha particles or protons bombarded targets of ^{12}C and (radioactive) ^{7}Be, and the reaction products were detected. However, as theoretical descriptions became more reliable, it became clear that the accuracy of these results and their extrapolations to astrophysical energies were inadequate. Systematic differences among various data sets were also a problem. This led to new approaches to these determinations.

For the $^{12}C + ^{4}He$ case, higher energy indirect experiments such as (^{7}Li, t) that transferred (added) alpha particles to ^{12}C provided information about the properties of the important nuclear states in ^{16}O. Additional information was obtained from the beta-decay of the radioactive nucleus ^{16}N. Elastic alpha scattering measurements gave information about the interference effects between the different resonances. High-energy electron beams incident on ^{16}O are being used to study the inverse of this reaction. And in the near future, it may be possible to study the reaction in reverse using intense beams of photons bombarding ^{16}O. For the ^{7}Be + p case, a high-energy beam of radioactive ^{8}B bombarded a heavy target and was broken up by the electric field of the target. Such Coulomb-breakup reactions are equivalent, by detailed balance, to the inverse process and can be used to study capture reactions involving short-lived nuclei such as ^{8}B. The $^{7}Be + p \rightarrow ^{8}B + \gamma$ reaction is nonresonant, and studies of reactions that transfer protons and measure asymptotic normalization coefficients (ANC) yielded the cross section at astrophysical energies; this technique has a wide range of applications. The reaction is also being studied directly, both with protons and with beams of radioactive ^{7}Be ions using inverse kinematics.

Both direct and indirect methods and a variety of accelerators have been used for the above studies. These include low energy and tandem accelerators of protons, alpha particles, ^{12}C, and ^{7}Be; ^{16}N ions produced by an ISOL facility and tandem accelerators; high energy beams of radioactive ^{8}B produced using nuclear reaction and fragmentation techniques; high energy beams of ^{7}Be and ^{10}B from a stable beam cyclotron; and medium energy electron beams. Beams of gamma rays from the free-electron-laser facility HIGS can provide high luminosities for measurements of (inverse) radiative capture cross sections. One need not understand all these approaches in detail to realize that a variety of accelerators will contribute in an important way to such measurements. In addition, high power lasers can produce plasmas with temperatures and densities similar to those in stars, and present an opportunity to study nuclei in stellar-plasma conditions.

Some of the facilities that are needed are shown in the following tables, categorized by reaction or site. In examining these tables several points should be kept in mind. First, a type of facility is grayed-in if it is useful for studying a given class of reaction. Several types of facilities will usually be required to study all reaction of a given class. Second, several approaches to a measurement are often necessary for understanding the systematic uncertainties that plague these difficult measurements. And third, the tables are almost certainly incomplete – new approaches will be developed and shown to be useful for these measurements or there may have been oversights. The overall message of the tables is that a variety of approaches are required and appropriate for studies in nuclear astrophysics.

	Stellar Burning				Explosive Burning				
FACILITY/REACTIONS	**H**	**He**	**HI**	**s**	**r**	**rp**	**αp**	**γ**	**ν**
Low-E Stable Beam									
High-E Stable Beam									
RIB-ISOL									
RIB-Fragmentation									
Spallation n (ν) source									
Free Electron Laser									

This table shows the experimental methods that are useful for attacking a particular type of problem. The symbols H, He, and HI refer to hydrogen burning, helium burning and heavy-ion burning in stars in quasistatic burning phases. The s-process is denoted by "s". The symbols r, rp, αp, γ, υ refer to the r-process, rp-process, αp-process, gamma process, and the neutrino process. All of these occur in explosive environments, such as in supernovae or binary systems.

SITE	**Big Bang**	**Cosmic Rays**	**Super-novae**	**Neutron Stars**
Low-E Stable Beam				
High-E Stable Beam				
RIB-ISOL				
RIB-Fragmentation				
Neutrino sources				

This table gives similar information for other sites. Supernovae here refers to the various weak process that occur in and near supernova cores, including the electron capture that makes the core neutron-rich, and neutrino breakup processes. It also includes explosive versions of H, He and HI reactions noted in the table above.

XIV. EQUIPMENT NEEDS FOR LABORATORY ASTROPHYSICS

The strong scientific case for studying the role of nuclei in the cosmos warrants a concerted experimental effort. Although some experiments can be done with existing devices, many will require a new generation of experimental equipment. Conceptual designs exist for some of this equipment, but development activities will be required for gamma ray and neutron detection, highly integrated electronics, and high-density gas or liquid targets. Stable beam experiments must often push the limits of low cross sections and low background rates. Radioactive beam experiments must push the limits of efficient operation with extremely low beam intensities. This section outlines the equipment that is needed to address these limits.

We have concentrated on detectors and equipment that will be used by a variety of experimenters, for a variety of experiments at a given facility. We do not discuss the large detectors necessary for neutrino detection or neutrino-induced experiments. These devices are important for an understanding of astrophysical phenomena but have a cost comparable to many accelerator facilities, are special purpose in nature, and must generally be justified on an individual basis. We have also cast much of the discussion in terms of the requirements of experiments that use radioactive beams, simply because they are less familiar. The general requirements are similar for experiments with low-energy stable beams, although the details of the detection devices will differ.

General requirements
The broad range of experimental conditions with respect to energy, mass, and intensity, requires a correspondingly broad array of experimental apparatus. Most of the radioactive beam experiments and many with stable beams will be done in inverse kinematics, where a lighter target is bombarded with a heavier beam. Inverse kinematics experiments require high granularity charged particle and gamma-ray detectors to compensate for the large kinematic or Doppler shifts. In addition, the decay of scattered radioactive beam particles will produce a high background rate in particle and gamma-ray detectors, which again requires segmented detector systems. In experiments with low intensity beams, detector systems must cover a large fraction of the total solid angle. Selection of the reactions of interest in experiments with impure beams (a common situation) requires coincident detection of the outgoing particles with good mass and charge identification. For all these reasons, requirements for experimental equipment differ from those of the current generation.

Gamma-ray detectors
Gamma-ray detection will be important in many experiments. Arrays of clustered germanium detectors can be configured in a compact geometry and can be used for gamma detection in decay studies, or at the focal plane of a mass separator for isomer studies, or for beta-gamma-gamma coincidence experiments. But they do not have sufficient segmentation for many purposes. Highly segmented arrays such as GAMMASPHERE lack the necessary overall efficiency and position resolution. Approaches that track events in germanium detectors as in the next-generation approaches typified by GRETA (Gamma-Ray Energy Tracking Array) or GARBO (Gamma-Ray Box) are required. Devices with similar characteristics could increase gamma-ray detection efficiency to 50% from around 10% and

will be able to work in high- background environments. The position resolution would be 2 mm compared to the current 20 mm, allowing adequate Doppler correction.

Particle detectors

The common use of inverse kinematic techniques affects the nature of required particle detectors. In the many cases where direct measurements of reaction rates are not possible, these rates must be inferred from the resonance or continuum parameters determined indirectly from nuclear reactions. The targets will typically be light nuclei, often protons or deuterons. In inverse kinematics the light recoil ions are found near 0 degrees for (p, d)-like (pick-up) reactions, near 90 degrees for inelastic and elastic scattering, and near 180 degrees in (d, p)-like (stripping) reactions. The detector must have excellent position resolution to allow correction for the large kinematic shift with angle. The low intensity of secondary beams requires that the array cover the angular range of interest, typically about 50 degrees in the laboratory. A large area array of silicon strip detectors could meet these needs; its design should be modular and flexible to allow for a variety of uses. Silicon strip detector technology will also be employed in the focal plane detector systems of recoil separators and magnetic spectrographs. Due to the importance of this technology, immediate development of highly integrated electronics is a high priority; no commercially available electronic systems provide the required resolution in energy (20 keV) and time (150 ps), along with other necessary features.

Many experiments will require the detection of neutrons. These include beta-delayed neutron decay of nuclei on the r-process path, (d, n) stripping reactions to determine proton spectroscopic factors for nuclei involved in novae and X-ray bursts, (p, n) reactions for the determination of weak interaction rates, and Coulomb-breakup experiments to infer (n, γ) reaction rates from detailed balance. The detection of high-energy neutrons typically requires a large area detector with moderate resolution, such as the existing neutron walls at fragmentation facilities. However, inverse kinematics experiments involve low energy neutrons and require high granularity. For this case, evaluation of various prototype detectors is required before a decision on detector type can be made. Both detector arrays and walls will probably be important.

Magnetic detectors

Several types of magnetic devices will be required. Studies of radiative capture reactions (with both stable and radioactive beams) require mass separators with a modest solid angle and high beam rejection capability, up to at least 10^{15}:1. These devices can be designed for relatively low rigidity, and should be flexible and allow various optical configurations. Target arrangements should allow for gamma-ray detection and the use of gas cell and gas jet targets. Nuclear structure studies at future radioactive ion beam facilities, necessary to test nuclear models used in the prediction of r- and rp-process nuclei, will require a large acceptance, high mass-resolving power (>350) separator. The target area should allow for the use of nearly 4π gamma-ray and particle detector arrays. Beam rejection should be maximized to allow clean experiments in the focal plane.

Another required device is a magnetic spectrograph with large solid angle (20 to 100 msr) and good energy resolution (1 part in 10^4). This device will be critical for transfer reaction studies at lower energy to extract information on parameters for resonant reaction rates, and for breakup studies at higher energies to measure ground-state structure and Coulomb-breakup cross sections.

Other instrumentation

Many of the reactions of astrophysical interest require targets of pure hydrogen and helium isotopes for study of hydrogen or alpha-induced reactions. Examples are radiative proton capture by light nuclei and (d, p) reactions on neutron-rich nuclei that can be studied most easily in inverse kinematics. The targets should be windowless and should allow operation with many different gases. It would be desirable to have target densities of $10^{19}/cm^2$ in order to compensate for weak beam intensities, but this will be difficult to achieve, especially for light gases. For higher energy experiments, thin, uniform liquid hydrogen targets will be useful; significant efforts will be necessary develop such targets.

Certain specialized equipment will be required for particular experiments. For example, ion traps will be used for precision mass measurements; and germanium detector arrays and tape transport (or equivalent means of removing radioactive ion buildup) will be required for decay-spectroscopy studies. Implantation stations and chemical separation stations will be required for producing the radioactive targets that may be preferable to radioactive beams for half-lives greater than about one day.

In many cases, especially for studies related to the s- and p-process, targets of rare or separated isotopes are required. The considerable cost or unavailability of such material limits the experimental opportunities.

A summary of some of these equipment needs is given in the table on the following page.

	LE-SB	**HE-SB**	**RIB ISOL**	**RIB FRAG**	**SNS**	**FEL**
Gamma array-segmented	■	■	■	■	■	
Silicon-Strip Arrays	■	■	■	■	■	■
Neutron Array	■	■	■	■		■
Spectrograph		■	■	■		■
Mass Separator	■		■	■		
Gas/Liquid Targets	■	■	■	■		
Radioactive Targets	■				■	
Traps			■	■		

This table shows the general types of apparatus that will be required by experiments with various types of facilities. Of course, the precise nature of a particular device will differ depending on the facility. Here LE-SB and HE-SB stand for low and high energy stable beam facilities; RIB ISOL and RIB FRAG stand for the two types of radioactive beam facilities (ISOL and Fragmentation); SNS stands for Spallation Neutron Source but for some purposes includes linacs and other neutron sources; FEL stands for Free Electron Laser.

XV. OUTLOOK

It is an exciting time for nuclear astrophysics. There are opportunities to reach a new level of understanding of nucleosynthesis in the big bang, of the evolution of stars, and of explosive events such as supernovae, novae, x-ray-bursts, x-ray pulsars and neutron star mergers. An exquisitely detailed record of these events will flow from new astronomical observatories. Nuclear physics is so inextricably involved in astronomical phenomena, however, that only with a much better knowledge of nuclei and nuclear reactions can we obtain a deep understanding of these phenomena.

Fortunately, promising new facilities exist or are on the horizon. New radioactive beam facilities will produce elements previously made only in stars and elucidate those of their properties important for cosmic phenomena. Stable beam accelerators with exceptional intensity and cleanliness will study nuclear reactions at energies close to those found in stellar environments. Powerful neutron sources will delineate processes that create the heavy elements. More powerful detectors of neutrinos from the sun and supernovae will provide information on neutrino properties, and on the role of neutrinos in explosive processes.

With wise investment of our resources, great strides in our knowledge of the cosmos should be possible in the near future. We can anticipate finding the sources of energy density in the universe, based on nucleosynthesis in the big bang, measurements of the cosmic background radiation, and measurements of the acceleration of the cosmic expansion, using Type Ia supernovae as standard candles. We will probably have a solution of the solar neutrino problem and a picture of the nature of neutrinos: the number of neutrino types and their masses. We can expect to have assembled the requisite combination of computational power and nuclear physics knowledge to model supernova explosions. We should know where the heavy elements are formed and understand the processes that make them. We should have understood the complex mixing and mass loss dynamics, which accompanies late stellar evolution. We should have an improved understanding of the structure of neutron stars and of how their properties are modified by nuclear burning on their surfaces in binary systems. With luck, we will have constructed a detector for supernova neutrinos and have observed a (rare) supernova explosion.

We can anticipate further challenges. Given the explosive growth of terrestrial and satellite-based observatories, it seems certain that new phenomena will be observed and that new knowledge of nuclear physics will be crucial to understanding them.

APPENDIX A: PROGRAM

Town Meeting on Opportunities in Nuclear Astrophysics

PROGRAM

Sunday June, 6

7-9 p.m. Reception at the Morris Inn

Monday June, 7

Room 127 - Nieuwland Science Hall:

8:30	Welcome - Jeffrey C. Kantor, Vice President and Associate Provost, University of Notre Dame
8:40	*Introduction* - J. Kolata, Univ. of Notre Dame

Chair – C. Barnes

8:50-9:20	*New observational evidence for nucleosynthesis* - J. Truran, Univ. of Chicago
9:30-9:45	*NuPECC recommendations in nuclear astrophysics* - F. Thielemann, Univ. of Basel
9:50-10:20	*Creation of the lighter elements* - M. Turner, Univ. of Chicago
10:30	Coffee

Chair – B. Balantekin

11:00-11:30	*The solar neutrino problem and supernova neutrino detection* H. Robertson, Univ. of Washington
11:40 –12:10	*Quasistatic evolution and nucleosynthesis in massive stars* - R. Hoffman, LLNL
12:20-1:30	Lunch (South Dining Hall)

Chair – S. Shore

1:30-2:00	*Neutron sources and the s-process in red giant stars* - R. Gallino, Univ. of Torino

2:10-2:40	*Explosions in binary systems* - S. Starrfield, Arizona State
2:50-3:20	*The rp-process in X-ray bursters and X-ray pulsars* - H. Schatz, GSI
3:30	Coffee

Chair-J. Lattimer

4:00-4:30	*Supernova evolution* - T. Mezzacappa, ORNL
4:40-5:10	Supernova nucleosynthesis - F. Thielemann, Univ. of Basel
5:20-5:50	*Nuclear physics in the r-process* - K.-L. Kratz, Univ. of Mainz
6:30	Dinner in the working group rooms
7:00-9:00	**Working Group Session I (NSH - Nieuwland Science Hall)**

* Group #1:	123 NSH -	Data needs for stellar burning process (A. Champagne, P. Koehler)
* Group #2:	180 NSH -	Data needs for explosive H/He burning (M. Smith, H. Schatz)
* Group #3:	284 NSH -	Data needs for supernova explosions (K. Rykaczewski, Y.Z. Qian)
* Group #3a:	415 NSH -	Neutron stars and the nuclear equation of state (U. Garg, M. Prakash)
* Group #4:	404A NSH -	Data needs for big-bang nucleosynthesis, cosmic rays and the origin of rare isotopes (R. Boyd, A. Westphal)
* Group #5:	184 NSH -	Data needs to understand nuclear structure effects (A. Aprahamian, W. Nazarewicz)
* Group #6:	182 NSH -	Nuclear theory needs (B.A. Brown, R. Wiringa)

Tuesday June, 8

Room 127 - Nieuwland Science Hall:

Chair – M. Thoennessen

8:30-9:00	*Opportunities and Challenges for Nuclear Theory* - W. Haxton Univ. of Washington
9:10-9:35	*Opportunities with low energy accelerators* - M. Wiescher, Univ. of Notre Dame

9:40-10:05 *Opportunities with neutron sources* - F. Käppeler, Karlsruhe

10:10 Coffee

Chair – C. Davids

10:40-11:05 *Opportunities with ISOL facilities* - M. Smith, ORNL

11:10-11:35 *Opportunities with fragmentation facilities* - B. Sherrill, MSU/NSCL

11:40-12:05 *The need for indirect measurements* - A. Champagne, Univ. of North Carolina

12:10-12:35 *Experimental equipment needs* - I.Y. Lee, LBL

12:45-1:30 Lunch (South Dining Hall)

1:30-3:30 **Working Group II (NSH - Nieuwland Science Hall; O'Shag - O'Shaughnessy Hall)**

* Group #7:	284 NSH -	Indirect experimental approaches (P. Parker, B. Tribble)
* Group #8:	207 O'Shag -	Opportunities with real and virtual photons (M. Gai, H. Weller)
* Group #9:	123 NSH -	Opportunities and instruments for radioactive beam facilities (J. Kolata, E. Rehm)
* Group #10:	180 NSH -	Opportunities and instrumentation for low energy stable beam facilities (C. Brune, M. Hofstee)
* Group #11:	208 O'Shag -	Opportunities and instrumentation for neutron facilities (B. Haight, P. Koehler)
* Group #12:	415 NSH -	Weak interactions and neutrino detectors (H. Robertson, A. Garcia)

Chair – S. Austin

3:30-3:40 *Nuclear Data Database* - P. Parker, Yale

3:45 *Reports of Working Groups* (10 min. each) coffee will be available

6:00 Wrap-up

APPENDIX B: ATTENDEES

There were 174 attendees from 68 institutions, 52 in the U.S.

Aguilera	Eli	Inst. Nac. Investigaciones Nucl. (Mexico)
Ajzenberg-Selove	Fay	U. Pennsylvania
Alahari	Navin	NSCL/Michigan State
Andrzejewski	Jozef	ORNL/Univ. of Lodz (Poland)
Anthony	Don W.	NSCL/Michigan State
Aprahamian	Ani	Notre Dame
Austin	Sam M.	NSCL/Michigan State
Azhari	Afshin	Cyclotron Inst./Texas A&M
Baktash	Cyrus	ORNL
Balantekin	Baha	U. Wisconsin-Madison
Barnes	Charles A.	Caltech
Baumann	Thomas	NSCL/Michigan State
Beaulieu	Luc	IUCF
Becchetti	Fred D.	U. Michigan
Bernstein	Lee A.	LLNL
Bertulani	Carlos A.	Univ. Fed. do Rio de Janeiro (Brazil)
Blackmon	Jeff C.	ORNL
Boyd	Richard N.	Ohio State
Brenner	Daeg S.	Clark University
Britt	Harold C.	U.S. Dept. of Energy
Brown	Alex	NSCL/Michigan State
Brune	Carl R.	U. North Carolina-Chapel Hill
Bulgac	Aurel	U. Washington
Caggiano	Jac	ANL
Calaprice	Frank	Princeton Univ.
Champagne	Arthur E.	Univ. North Carolina
Chavez	Efrain R.	Instituto de Fisica/UNAM (Mexico)
Cherubini	Silvio	IPN/Univ. Catholique de Louvain (Belgium)
Clement	Ralph R.	NSCL/Michigan State
Collon	Philippe A.	Inst. für Rad. und Kernphysik (Austria)
Connell	James J.	U. Chicago
Couture	Aaron J.	Notre Dame
Culp	Fred	Tennessee Tech.
Daly	Jason T.	Notre Dame
Davids	Barry S.	NSCL/Michigan State
Davids	Cary N.	ANL
Davis	Andrew M.	U. Chicago
Dean	David J.	ORNL
DeBraeckeleer	Ludwig	Duke Univ.
DeSouza	Romualdo	Indiana Univ.
Engel	Jonathan	Univ. North Carolina
Fowler	Malcolm M.	LANL

Fox	John D.	Florida State
Freeman	Charlie G.	SUNY Geneseo
Frekers	Dieter	Univ. Münster (Germany)
Frisch	Priscilla	U. Chicago
Gai	Moshe	U. Connecticut
Gallino	Roberto	Dipt. di Fisica Generale/Univ. Torino (Italy)
Galonsky	Aaron	NSCL/Michigan State
Garcia	Alejandro	Notre Dame
Garg	Umesh	Notre Dame
Gelbke	Claus-Konrad	NSCL/Michigan State
Giesen	Ulrich	Notre Dame
Gledenov	Yuriy M.	ORNL/JIHIR-UT (Russia)
Goerres	Joachim	Notre Dame
Goodman	Charles D.	IUCF
Gould	Chris	N. Carolina State U/TUNL
Grimes	Steven M.	Ohio Univ.
Gross	Carl J.	ORISE/ORNL
Guber	Klaus H.	ORNL
Guimaraes	Valdir	Notre Dame
Haight	Robert C.	LANL
Halderson	Dean W.	Western Michigan
Hale	Gerald M.	LANL
Harss	Boris	ANL
Haxton	Wick	U. Washington
Heckman	Paul R.	NSCL/Michigan State
Hencheck	Michael	U. Wisconsin - Green Bay
Henning	Walter F.	ANL
Hix	William R.	U. Tennessee/ORNL
Hoffman	Robert D.	LLNL
Hofstee	Mariet A.	Colorado School of Mines
Horowitz	Charles J.	Indiana Univ.
Howes	Ruth H.	Ball State
Islam	Mohammed	Ball State
Janssens	Robert V.	ANL
Jiang	Cheng Lie	ANL
Jose	Jordi	Univ. Politecnica de Catalunya (Spain)
Kaeppeler	Franz	Forschungszentrum Karlsruhe (Germany)
Karwowski	Hugon J.	Univ. North Carolina
Keister	Bradley D.	NSF
Kemper	Kirby W.	Florida State
Koehler	Paul E.	ORNL
Kolata	James J.	Notre Dame
Kozub	Raymond L.	Tennessee Tech.
Kratz	Karl-Ludwig	Inst. Kernchemie/U. Mainz (Germany)
Kumar	Krishna	Tennessee Tech.

Lacey	Roy	SUNY Stony Brook
Lande	Kenneth	U. Pennsylvania
Lattimer	James M.	SUNY Stony Brook
Lee	I-Yang	LBNL
Lister	Kim	ANL
Liu	Tianxiao	NSCL/Michigan State
Liu	XiaoDong	NSCL/Michigan State
Lizcano	David	Inst. Nac. Investigaciones Nucl. (Mexico)
Lofy	Patrick A.	NSCL/Michigan State
Luke	John	LLNL
Lynch	Bill	NSCL/Michigan State
Mantica	Paul	NSCL/Michigan State
Martinez-Quiroz	Enrique	Inst. Nac. Investigaciones Nucl. (Mexico)
Massey	Thomas N.	Ohio Univ.
Mathews	Grant J.	Notre Dame
McEllistrem	Marcus T.	U. Kentucky
Mezzacappa	Anthony	ORNL
Morrissey	David J.	NSCL/Michigan State
Mukhamedzhanov	Akram	Texas A&M
Murphy	Alexander S.	Ohio State
Nakamura	Takashi	NSCL/Michigan State
Nazarewicz	Witold	U. Tennessee
Olsen	Michele	SUNY Geneseo
Ortiz	Maria-Esther S.	Inst. de Fisica, National U. Mexico
Pancella	Paul	Western Michigan
Parker	Peter	Yale
Peaslee	Graham	Hope College
Peterson	Donald	Notre Dame
Piechaczek	Andreas	Louisiana State
Pieper	Steven C.	ANL
Prakash	Madappa	SUNY Stony Brook
Prior	Richard M.	N. Georgia College & State U/TUNL
Prisciandaro	Joann I.	NSCL/Michigan State
Qian	Yong-Zhong	LANL
Rapaport	Jack	Ohio Univ.
Ravenhall	D. G.	U. Illinois/Urbana-Champaign
Rehm	Ernst K.	ANL
Ressler	Jennifer-Jo	U. Maryland/ANl
Robertson	Hamish	U. Washington
Rundberg	Robert S.	LANL
Runkle	Bob C.	Univ. North Carolina/TUNL
Rykaczewski	Krzysztof P.	ORNL/Physics Division
Santi	Peter A.	Notre Dame
Sawyer	Raymond F.	U. California-Santa Barbara
Schatz	Hendrik	GSI (Germany)

Schiffer	John P.	ANL
Schwartz	Brook	SUNY Geneseo
Seabury	Edward H.	LANL
Segel	Ralph	Northwestern
Serot	Brian D.	Indiana U.
Sherrill	Bradley M.	NSCL/Michigan State
Shore	Steven	Indiana U.-South Bend
Shotter	Alan	Edinburgh Univ. (Scotland)
Siemssen	Rolf H.	ANL
Smith	Donald L.	ANL
Smith	Michael S.	ORNL
Sonzogni	Alejandro A.	ANL
Soramel	Francesca	Universita' di Udine (Italy)
Starrfield	Sumner	Arizona State
Stephan	Andreas E.	Triangle U. Nuclear Laboratory
Strayer	Michael R.	ORNL
Tan	Wanpeng	NSCL/Michigan State
Ternovan	Christopher	Wittenberg Univ.
Thielemann	Friedrich K.	Univ. of Basel (Switzerland)
Thoennessen	Michael R.	NSCL/Michigan State
Tischhauser	Paul D.	Notre Dame
Tribble	Robert E.	Texas A&M
Truran	Jim	U. Chicago
Tryggestad	Erik J.	NSCL/Michigan State
Tsang	Betty	NSCL/Michigan State
Tsentalovich	Genya	MIT/Bates
Turner	Michael S.	U. Chicago
Ullmann	John L.	LANL
Van Wormer	Laura A.	Hiram College
Verde	Guiseppe M.	NSCL/Michigan State
Voytas	Paul A.	Wittenberg Univ.
Walters	William B.	U. Maryland
Weber	Fridolin	LBNL
Weil	Jesse L.	U. Kentucky
Weller	Henry R.	TUNL/Duke Univ.
Westphal	Andrew J.	U.C. Berkeley
Wiescher	Michael	Notre Dame
Winger	Jeff A.	Mississippi State
Wiringa	Robert	ANL
Wu	Jianshi	Fayetteville State U.
Xu	Hushan	NSCL/Michigan State
Zganjar	Edward F.	Louisiana State

APPENDIX C: STEERING AND WRITING COMMITTEES

Steering Committee
Sam Austin
Richard Boyd
Art Champagne
Wick Haxton
Kevin Lesko
Peter Parker
Ernst Rehm
Michael Smith
Robert Tribble
James Truran
Michael Wiescher

Writing Committee
Sam Austin
Richard Boyd
Art Champagne
Wick Haxton
Paul Koehler
Kevin Lesko
Peter Parker
Ernst Rehm
Brad Sherrill
Michael Smith
Robert Tribble
James Truran
Michael Wiescher

Consultants
Ani Aprahamian
Andrew Davis
C. Konrad Gelbke
Franz Kaeppeler
Grant Mathews
Filomina Nunes
Anthony Mezzacappa
Hendrik Schatz
Steve Shore
Friedrich-Karl Thielemann
Fridolin Weber