



International Atomic Energy Agency Nuclear Data Section  
Advisory Group Meeting on Long Term Needs for Nuclear Data  
Vienna, Austria, Nov. 28 – Dec. 3, 2000

## **NUCLEAR DATA NEEDS IN NUCLEAR ASTROPHYSICS: CHARGED-PARTICLE REACTIONS**

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### **Abstract**

Progress in understanding a diverse range of astrophysical phenomena - such as the Big Bang, the Sun, the evolution of stars, and stellar explosions - can be significantly aided by improved compilation, evaluation, and dissemination of charged-particle nuclear reaction data. A summary of the charged-particle reaction data needs in these and other astrophysical scenarios is presented, along with recommended future nuclear data projects.

### **1 Importance of Nuclear Data in Astrophysics Studies**

Nuclear astrophysics involves the study of the origin of the elements and the evolution of the astrophysical sites where this synthesis occurs. Systems as diverse as the early Universe, the interstellar medium, red giant stars, novae, and supernova explosions are the focus of many vigorous observational, theoretical, and laboratory research programs worldwide. These programs address some of the most interesting questions in nature: What are the origins of the elements that make up our bodies and our world, that make life on earth possible? How did the solar system, the sun, the stars, and the galaxy form, and how do they evolve? What is the total density of matter in the universe, and will the universe eventually collapse or expand forever? Nuclear data is the physical basis for models used to address these questions. It is also needed to interpret a wealth of new observations by ground-based telescopes such as the Keck Telescopes, by space-borne observatories such as the Hubble Space Telescope and the Chandra X-Ray Observatory, and by large subterranean detectors such as the Sudbury Neutrino Observatory and SuperKamiokande.

A diverse set of nuclear data is required to model the composition changes and energy release in a wide range of astrophysical environments. For example, rates of fusion reactions, transfer reactions, and nuclear decays are all needed, as are nuclear masses. Given the predominance of H and He in the Universe, many of the nuclear reactions occurring in astrophysical environments are induced by charged particles. Where available, the relevant nuclear reaction rate information is derived from laboratory measurements. For thousands of reactions, however, there is little experimental data. Some of these rates are calculated using theoretical analyses of indirect measurements and nuclear structure information such as excitation energies, spins and parities, resonance decay modes, and ground state half-lives. Other rates are calculated using statistical reaction models such as Hauser-Feshbach.

There have been a number of exciting advances in laboratory nuclear physics, including the availability of beams of radioactive nuclei, the ability to measure solar fusion reactions at their appropriate stellar energy in underground low-background laboratories, and sophisticated arrays of high-resolution gamma-ray and charged-particle detectors. Such advances, coupled with the evolution of fast, inexpensive computers, has enabled

extremely complex astrophysical calculations of increasing realism to be carried out. For example, calculations coupling the time-dependent synthesis of hundreds of isotopes via thousands of linking reactions with multi-dimensional simulations of stellar and explosive environments are now beginning. These new codes require significantly more, and more accurate, nuclear data than ever before to keep pace with the stunning new capabilities of the Hubble, Chandra, Keck, and other observatories. Progress in many fundamental problems in astrophysics requires the best predictive power of astrophysical models.

In many instances, this predictive power has a strong dependence on the input nuclear data. There are numerous examples of the significant impact that new, more precise assessments of nuclear data can have on astrophysical studies. One example is the rate of the  ${}^3\text{H}(\alpha,\gamma){}^7\text{Li}$  reaction producing  ${}^7\text{Li}$  during the Big Bang. The standard Big Bang Nucleosynthesis (BBN) model predictions for  ${}^7\text{Li}$  production are extremely sensitive to the model's one "free" parameter - the amount of "normal" matter in the universe (the baryon density) - as well as to the input nuclear physics. Consequently, comparisons of the primordial  ${}^7\text{Li}$  abundance inferred from observations to BBN model predictions allows a constraint to be put on the amount of normal matter in the universe. An evaluation [1] of the rate of the  ${}^3\text{H}(\alpha,\gamma){}^7\text{Li}$  reaction was a factor of two lower at temperatures corresponding to the Big Bang than previous work. When put into a BBN model, this resulted in a production of  ${}^7\text{Li}$  which was 20 % lower than previous model predictions. When compared to observations, this resulted in a limit on the baryon density of the universe which was 50 % higher than the previous limits. Therefore, an improvement in one nuclear reaction rate out of the many used in Big Bang models resulted in increasing the estimate of the amount of material in the Universe by 50 %.

Numerous other cases of the critical role of nuclear data in astrophysical models can be cited - many of them involving charged-particle reactions. For example, there is a very strong dependence of the abundances produced in supernova explosions on the value of the  ${}^{12}\text{C}(\alpha,\gamma){}^{16}\text{O}$  reaction rate [2]. This rate, one of the most important in all of nuclear astrophysics, determines the ratio of C to O after core He burning, and determines the subsequent evolution of a massive star into a neutron star or black hole. For this reason, it is the subject of much experimental and theoretical attention. The rates of reactions that produce and destroy  ${}^{26}\text{Al}$  have a significant impact [3] on the interpretation of observations of  ${}^{26}\text{Al}$  in the interstellar medium [4] and in meteorites [5]. The uncertainty in the rate of the  ${}^7\text{Be}(p,\gamma){}^8\text{B}$  reaction determines the current uncertainty in neutrino oscillation "solutions" to the Solar Neutrino Problem [6]. Uncertainty in the rates of proton-capture reactions on radioactive isotopes contribute to a factor of ~300 uncertainty in the production of the long-lived radioisotope  ${}^{18}\text{F}$ , which can act as an observational tracer of nova explosions [7]. This uncertainty makes it difficult to determine the sensitivity of multi-million dollar observatories for measuring gamma rays from these explosions. These are only a few examples of the significant impact that nuclear data can have on nuclear astrophysics studies.

## 2 Motivation for Expanded Nuclear Data Activities in Astrophysics

The user community for nuclear astrophysics data consists of scientists using a combination of sophisticated astrophysics modeling codes to decipher the most detailed, precise, and costly astrophysical observations ever made. Measurements in the nuclear laboratory form the empirical foundation for the current models of element synthesis. Astrophysics models therefore have a crucial dependence on the completeness, precision, and timeliness of substantial quantities of input nuclear data. Evaluations of nuclear reaction data for astrophysics was initiated and nurtured by Willy Fowler and his collaborators (see, e.g. [8,9]), but unfortunately he and his program are no longer with us. There is currently little manpower devoted to continuing his effort. Indeed, there is a growing recognition that the data needs of the research community cannot be provided by the voluntary efforts of any single research group alone. The little voluntary work that is being done is fragmentary, poorly coordinated, and most importantly, not nearly enough. The result is a developing break down in communication

between scientists in the nuclear laboratory and those using the data in their codes. This results in an extremely poor utilization of important, difficult, and costly nuclear physics experiments by the astrophysicists for whom they were measured.

There is also a growing recognition that the data needs in nuclear astrophysics have a strong overlap with nuclear data needs in other basic and applied nuclear physics fields. Furthermore, the nuclear data community has developed considerable expertise and technical resources [10] that could be used to address some of these astrophysics data needs. In fact, some resources in the U.S. nuclear data community have been shifted towards work in this frontier field. However, there is currently no systematic, coordinated, long-term solution in the U.S. or internationally to the problem of providing the best nuclear data in forms needed for astrophysical models.

Indeed, the current situation in nuclear astrophysics parallels the situation in reactor physics and nuclear weapons design in the U.S. 25 years ago. Astrophysicists often have their own sets of nuclear data produced by the individual scientist from scattered data collections of their choosing. This makes it difficult to compare results, and also makes the uniform updating of codes with new evaluations difficult. Significant progress was realized in these other fields when standardized sets of data were widely available to researchers, allowing the model codes to be decoupled from the input data. While some astrophysicists will always prefer to use proprietary data sets, a set of freely available, regularly updated, communal data sets would lead to a standardization that would help advance the field and would encourage the development and improvement of the input data sets themselves in a synergistic way.

There are, however, some difficulties in producing these data sets. For example, laboratory measurements often probe the astrophysical reactions of interest only indirectly. Relevant information (e.g., nuclear resonance widths and energies) must be extracted and used to calculate useful quantities such as reaction rates. This requires extra work before the data can be used in astrophysical models. Even when this work is done and published, it still must be evaluated, compared with other measurements, and disseminated to the community. For this and many other reasons, many of the existing sets of nuclear data for astrophysics studies are incomplete, both in their scope (e.g., not enough nuclides) and their depth (e.g., missing some crucial information). For example, some of the most sophisticated new astrophysical observations cannot be used to distinguish between competing astrophysical models without significantly improving calculations of uncertainties in model predictions. Uncertainties in the input nuclear physics, which are often not provided in available evaluated nuclear data sets, are required in order to calculate the uncertainties in model predictions of astronomical observables.

Dedicated effort is required to address all of these problems and to provide usable, accurate, and significant amounts of nuclear data in a timely fashion. A new initiative is required, and the benefit will be progress in many fundamental problems in nuclear astrophysics. The data stewardship activities which are needed include: making high-quality data evaluations, complete compilations, and timely and useful disseminations; and using nuclear reaction and structure models to extend existing measurements to unmeasured reactions, energy ranges, and isotopes.

### **3 Nuclear Data Used in Nuclear Astrophysics**

In general, astrophysical models require the rates of and energy released in nuclear reactions occurring in astrophysical sites [11]. Many of the relevant nuclear reactions are induced by charged particles because of the overwhelming presence of H and He in the Universe. The rates are derived from laboratory measurements of cross sections convoluted with the thermal (Maxwell-Boltzmann) relative velocity distribution of the interacting

particles. The released energies of the relevant reactions (Q-values) and nuclear masses are derived from measurements and calculations. The types of charged-particle reactions occurring in astrophysical scenarios include particle capture (fusion), particle exchange, particle transfer, spallation, and (to a lesser extent) three body reactions. Additionally, weak interactions (electron and positron decays and captures), photodisintegrations, and beta-delayed particle emissions occur. For example, heavy isotopes are synthesized from the fusion of lighter isotopes with the “fuel” (e.g., protons, alphas) present in stellar environments. The relevant energies of these reactions depend on the astrophysical site, but range from approximately 0.01 - 2 MeV/u for reactions with charged particles. The nuclides relevant for each of these reaction types varies greatly with the phenomenon studied. For example, charged-particle reactions on stable isotopes for masses up to the Fe group and beyond are important for massive star evolution, whereas reactions on radioactive isotopes near the proton drip line are important for explosive nucleosynthesis in novae, supernovae, and X-ray bursts. Details of important reactions in different scenarios are given in Section 4. There are a number of existing data sets relevant for nuclear astrophysics studies [10], some of which need significant expansion, updating, or other improvements. These data sets and projects for their improvement are discussed in Section 5.

Since the thousands of nuclear reactions occurring in some astrophysical environments cannot all be measured, nuclear models play a central role in providing the information needed for astrophysics models. Nuclear models, used to calculate the cross section and the energy release (Q-value) of unmeasured reactions, require substantial nuclear structure information as input, such as masses, the parameters of resonances near particle capture thresholds of the relevant isotopes, optical model parameters, one- and two-particle separation energies, and single-particle energy levels. Other quantities such as nuclear wave functions, level densities and partition functions are also required as input. The nuclear modeling needs for nuclear astrophysics will be discussed in a separate article in these proceedings.

## 4 Nuclear Data Needs for Specific Astrophysics Scenarios

A very diverse set of information on nuclear reactions and nuclear properties is required for nucleosynthesis models, and the particular information varies significantly for different astrophysical phenomena. Examples of the information needed for studies of the Big Bang, stellar evolution, stellar explosions, and other scenarios are given below.

### 4.1 Big Bang Nucleosynthesis

Approximately 3 minutes after the beginning of the Universe in the Big Bang, the temperature had cooled to roughly  $10^9$  K, enabling protons and deuterons to fuse to form deuterium and initiating the synthesis of nuclei up to  ${}^7\text{Li}$ . The twelve most important reactions in the synthesis of nuclei in homogeneous models of the early Universe are  ${}^1\text{H}(n,\gamma)\text{d}$ ,  ${}^2\text{H}(p,\gamma){}^3\text{He}$ ,  ${}^2\text{H}(d,n){}^3\text{He}$ ,  ${}^2\text{H}(d,p)\text{t}$ ,  ${}^3\text{He}(n,p)\text{t}$ ,  ${}^3\text{H}(d,n){}^4\text{He}$ ,  ${}^3\text{He}(d,p){}^4\text{He}$ ,  ${}^3\text{He}(\alpha,\gamma){}^7\text{Be}$ ,  ${}^3\text{H}(\alpha,\gamma){}^7\text{Li}$ ,  ${}^7\text{Be}(n,p){}^7\text{Li}$ ,  ${}^7\text{Li}(p,\alpha){}^4\text{He}$ , and the decay of the neutron [1]. These reactions have been recently evaluated at temperatures appropriate for the Big Bang (laboratory energies up to  $\sim 1$  MeV) [1,12]. Currently, the  ${}^1\text{H}(n,\gamma)\text{d}$ ,  ${}^2\text{H}(p,\gamma){}^3\text{He}$ ,  ${}^3\text{He}(\alpha,\gamma){}^7\text{Be}$ , and  ${}^7\text{Li}(p,\alpha){}^4\text{He}$  need additional work, along with a critical, statistically robust assessment of the uncertainties of all the important rates considering all previous measurements. These uncertainties are important because they are input into models employing a Monte Carlo technique to determine uncertainties in the synthesized abundances.

There are, however, models of the early universe where the phase transition from quarks and gluons to hadrons could possibly cause proton-rich and neutron-rich regions to form [13]. These Inhomogeneous Big Bang Nucleosynthesis (IBBN) models involve nuclear reactions on some light unstable isotopes which produce different abundances than in standard Big Bang models. Examples of important reactions are  ${}^8\text{Li}(\alpha,n){}^1\text{B}$  and

${}^8\text{Li}(\text{d},\text{n}){}^9\text{Li}$  [14], as well as neutron captures on neutron-rich isotopes of carbon. Recent observations of the spectrum of the cosmic microwave background radiation power spectrum [15] suggest a universal mass density that is consistent with some IBBN models but outside the range normally quoted for standard Big Bang models [16]. This suggests the importance of evaluating the nuclear reactions in IBBN models.

## 4.2 Evolution of Low Mass Stars

Stars are born when clouds of gas and dust in the interstellar medium gravitationally collapse and ignite nuclear reactions at their core. These reactions turn H into He and generate energy, preventing further gravitational collapse and causing the stars to shine [11]. Low-mass stars like our Sun burn hydrogen through sequences of reactions called the pp-chain, while those a few times the mass of the Sun burn hydrogen through the CNO cycles. These stars eventually exhaust their hydrogen fuel at the core - leaving behind a He core surrounded by a thin shell where H is burned and finally an outer convective layer. A rich nucleosynthesis occurs when these stars go through a thermally-pulsing asymptotic giant branch (TP-AGB) phase [18]. Some of the nuclides created are dredged up to the surface by convection and ejected into space via strong winds. There are significant uncertainties in the rates of a number of nuclear reactions such as  ${}^{14}\text{N}(\text{p},\gamma){}^{15}\text{O}$ ,  ${}^{15}\text{N}(\text{p},\gamma){}^{16}\text{O}$ ,  ${}^{17}\text{O}(\text{p},\gamma){}^{18}\text{F}$ , and  ${}^{17}\text{O}(\text{p},\alpha){}^{14}\text{N}$  occurring during this evolution. These uncertainties make it difficult to understand the time for core H depletion, the abundances of the C, N, and O isotopes, and other evolutionary aspects [17,18]. Reactions in the NeNa Cycle also occur in the hydrogen-burning shell, such as  ${}^{22}\text{Ne}(\text{p},\gamma){}^{23}\text{Na}$  and  ${}^{23}\text{Na}(\text{p},\gamma){}^{24}\text{Mg}$ , which need to be better understood to describe the observed abundances of Na isotopes on stellar surfaces. Similarly, in the MgAl Cycle, the  ${}^{25}\text{Al}(\text{p},\gamma){}^{26}\text{Si}$  and  ${}^{25}\text{Mg}(\text{p},\gamma){}^{26}\text{Al}$  reactions influence the abundance of Al isotopes observed on stellar surfaces and the amount of the long-lived radioactive isotope  ${}^{26}\text{Al}$  in the interstellar medium (observed by the Compton Gamma Ray Observatory) [4]. The  ${}^{12}\text{C}(\alpha,\gamma){}^{16}\text{O}$  reaction [19] determines C / O ratio after core He burning and thereby strongly influences the subsequent evolution of these stars. Improved measurements, theoretical calculations, and new evaluations are needed for this reaction. The  ${}^{13}\text{C}(\alpha,\text{n}){}^{16}\text{O}$  and  ${}^{22}\text{Ne}(\alpha,\text{n}){}^{25}\text{Mg}$  reactions are the source of neutrons for the s-process occurring in these stars, and the current large uncertainties in the  ${}^{22}\text{Ne}(\alpha,\text{n}){}^{25}\text{Mg}$  rate influences the production of elements heavier than Fe. The  ${}^{22}\text{Ne}(\alpha,\text{n}){}^{25}\text{Mg}$  reaction also influences the depletion of Ne - and therefore plays a role in the overproduction of Na in current stellar models.

## 4.3 Evolution and Explosions of Massive Stars

Stars with masses more than  $\sim 8$  times that of the Sun go through a number of burning phases (H, He, C, O, Ne, Si) at their core resulting in a core of Fe. This core then quickly undergoes gravitational collapse, changing the material to primarily neutrons and compressing the material to super-nuclear densities. The core rebounds, sending out a shock wave responsible for a violent explosion generating  $\sim 10^{51}$  ergs of energy in less than a second [20]. These explosions are most likely responsible for the synthesis of approximately half of the isotopes heavier than iron via the rapid neutron capture process (r-process). The current scenario has a series of alpha-induced reactions assembling nuclides up to mass 80 (the alpha-process), followed by fast (n, $\gamma$ ) reactions on neutron-rich unstable isotopes out to the dripline, all occurring in the high-entropy wind off the surface of the newly-formed protoneutron star created in the explosion [21]. Supernovae are also thought to be the site of the p-process, which creates heavy proton-rich stable nuclides most likely by photodissociation of heavier nuclides.

Understanding this model of a core collapse supernova and all the nucleosynthesis requires significantly improved nuclear physics, including many charged-particle reactions [22]. The nucleosynthesis is more sensitive to the pre-explosion star than to the details of the explosion mechanism. The  ${}^{12}\text{C}(\alpha,\gamma){}^{16}\text{O}$  reaction is the most crucial reaction for these studies [2], but there are many others. For example, screening effects at low energies need to be understood for the  ${}^{12}\text{C} + {}^{12}\text{C}$  reaction in pre-collapse core carbon burning. Also, p-induced &  $\alpha$ -induced reactions on C - Si nuclei influence the energy generated in CNO burning, the abundances of

stable nuclides such as  $^{17}\text{O}$ ,  $^{18}\text{O}$ , and  $^{22}\text{Ne}$ , and the abundances of long-lived radioisotopes such as  $^{26}\text{Al}$  and  $^{22}\text{Na}$ . The propagation of a supernova shock wave into the outer layers of the star may heat and compress material sufficiently to ignite brief occurrences of explosive burning [23]. The nuclear reactions involve captures of protons and alphas on proton-rich radioactive isotopes similar to those occurring in very hot novae or X-ray bursts (see Section 4.1). In the C-Si mass range, the reactions are not amenable to statistical model calculations because of the low level densities of the compound nuclei. Therefore, improved experiments and evaluations of individual reactions are needed.

For nuclides for  $14 < Z < 50$ , p-induced &  $\alpha$ -induced reactions on unstable & stable nuclides are needed for supernova models, and these can be treated with statistical model calculations since the level densities are often sufficiently high [22]. These reactions influence the explosive burning that may occur in outer envelopes of supernovae, p-process nucleosynthesis, (the beginning of) r-process nucleosynthesis, and the abundances of radioisotopes  $^{44}\text{Ti}$  and  $^{60}\text{Fe}$ . Improved knowledge of Gamow-Teller resonances in (p,n) reactions in Si - Ni mass range is needed to determine  $e^-$  capture rates, as well as better rates for ( $\alpha,\gamma$ ) reactions on  $\alpha$ -nuclei from  $^{28}\text{Si}$  -  $^{44}\text{Ti}$ . Furthermore, there is almost no experimental data on (p, $\gamma$ ) or ( $\alpha,\gamma$ ) reactions in the Gamow window of the p-process, for unstable or stable isotopes. Some experimental information, coupled to the best statistical model reaction calculations, are needed for work in this area.

## 4.4 Explosions in Accreting Binary Systems

### 4.4.1 Novae

Nova explosions are accretion-driven explosions caused by the transfer of mass from one star to a white dwarf companion star [24]. The mass transfer and subsequent rise in temperature and pressure can initiate a violent runaway thermonuclear explosion ( $\sim 10^{38}$ -  $10^{45}$  ergs released), resulting in the synthesis of elements up to mass  $\sim 40$  and their subsequent ejection into space. Novae are thought to be sources of nuclides such as  $^{13}\text{C}$ ,  $^{15}\text{N}$ , and  $^{17}\text{O}$  which are difficult to produce in other astrophysical environments. The explosion also influences the subsequent evolution of the binary star system. These catastrophic stellar events are characterized by extremely high temperatures ( $> 10^8$  K) and densities ( $> 10^3$  g/cm $^3$ ). Under such conditions, (p, $\gamma$ ) and ( $\alpha,\text{p}$ ) reactions can rapidly (on timescales of nanoseconds to minutes) produce unstable nuclei on the proton-rich side of the valley of stability. Any such nuclei (decaying via  $e^+$ -emission) produced with half-lives longer than, or comparable to, the mean time between nuclear reactions can potentially undergo subsequent nuclear processing.

Reactions on proton-rich radioactive nuclei are crucial in these explosions [25,23], producing abundances which are very different than those from the hydrogen burning occurring in non-explosive environments [26,27] and generating energy up to 100 times faster than in quiescent stars. Some radioactive nuclei (those with lifetimes greater than 100 s) synthesized in explosions may be carried by convection to the top of the envelope before they decay. Observations of the  $\gamma$  - ray lines (especially the 511- keV emission of  $^{18}\text{F}$ ) resulting from such radioactive decays in the envelope may provide stringent tests of nova models [28,29]. The  $\gamma$ -ray emissions depend sensitively on the amount of radionuclides synthesized by nuclear reactions in the explosion, which in turn depends on the rates of nuclear reactions on radioactive isotopes [30,31]. Examples of important reactions include  $^{17}\text{F}(\text{p},\gamma)^{18}\text{Ne}$ ,  $^{18}\text{F}(\text{p},\alpha)^{15}\text{O}$ ,  $^{19}\text{Ne}(\text{p},\gamma)^{20}\text{Na}$ ,  $^{20}\text{Na}(\text{p},\gamma)^{21}\text{Mg}$ ,  $^{21}\text{Na}(\text{p},\gamma)^{22}\text{Mg}$ ,  $^{22}\text{Na}(\text{p},\gamma)^{23}\text{Mg}$ , and  $^{25}\text{Al}(\text{p},\gamma)^{26}\text{Si}$  [25,32]. These can lead to hydrogen burning through the rapid proton capture process (rp-process), involving (p, $\gamma$ ) reactions near the proton dripline competing with  $e^+$ -decay and reaction cycles (e.g.,

the Ne-Na and Mg-Al cycles). The rates of such reactions on unstable isotopes are needed to understand the nova phenomenon. Even though evaluations of these reactions was listed as one of the top priorities by a steering committee on nuclear astrophysics data in 1996 [33], only a few reactions have been examined since that time. These evaluations can have significant impact on the interpretation of observations made by multi-million dollar astrophysical devices, especially those of the INTEGRAL satellite to be launched in 2002. The uncertainties of these rates are also needed because of the ability of Monte Carlo techniques to estimate uncertainties in the synthesized abundances from the input nuclear physics uncertainties [34].

#### 4.4.2 X-ray Bursts and X-ray Pulsars

Other accretion-driven phenomena important in astrophysics include X-ray bursts and X-ray pulsars. These can occur when material is accreted onto the surface of a neutron star. The temperatures and densities can reach over  $10^9$  K and  $10^6$  g/cm<sup>3</sup>, respectively [35,36], and the ensuing explosive hydrogen burning can synthesize isotopes with masses up to 80 - 100 or beyond [36,37,38] via reactions in the  $\alpha$ p- and rp-processes. Recent studies of nucleosynthesis in these violent explosions suggest that their X-ray luminosity and neutron star crust composition are influenced by the nuclear reactions (most involving proton-rich radioactive isotopes) used in the model [39]. For example, the rates of reactions in the sequence  $^{12}\text{C}(p,\gamma)^{13}\text{N}(p,\gamma)^{14}\text{O}(\alpha,p)^{17}\text{F}(p,\gamma)^{18}\text{Ne}(\alpha,p)^{21}\text{Na}(p,\gamma)^{22}\text{Mg}$  are crucial because they give the maximum flux of X-rays and serve as the gateway to the synthesis of heavier nuclei [36,40]. Properties of nuclei along the proton dripline are important, along with proton capture reaction rates, to understand these violent explosions.

#### 4.5 Other Astrophysical Environments

There are other astrophysical sites [37] - e.g., the accretion disk around black holes [40] - where temperatures and densities may be sufficient for explosive hydrogen burning to occur. In these environments, reactions on proton-rich radioactive isotopes may play an important role, as they do in novae and X-ray bursts. Supermassive stars [41,42] are another possible site of explosive H and He burning via reaction sequences such as  $p(p,e^+\nu)d(p,\gamma)^3\text{He}(\alpha,\gamma)^7\text{Be}(p,\gamma)^8\text{B}(\alpha,p)^{11}\text{C}(p,\gamma)^{12}\text{N}(e^+\nu)^{12}\text{C}$ . This sequence produces  $^{12}\text{C}$  via an alternate pathway to the slow triple-alpha process. This additional  $^{12}\text{C}$  can, via hydrogen burning through the Hot CNO cycles, generate sufficient energy to possibly alter the evolution of these exotic stars. The reactions involved include those in quiescent stellar hydrogen burning (but at higher temperatures) as well as those in explosive stellar hydrogen burning. There is a renewed interest in these stars because of the recent discovery of many supermassive black holes at the centers of galaxies.

### 5 Nuclear Data Sets for Nuclear Astrophysics

One example of charged-particle nuclear data sets which are extremely valuable for studies in nuclear astrophysics are collections of reaction rates derived from measured or calculated cross sections. These collections typically include rates as analytic functions of temperature and be parameterized in formats easily input into astrophysical models. A list of data sets available (up to 1995) can be found in ref. [10]. Examples include: the 1988 collection of Caughlan and Fowler [9] with 160 reactions; an update of 86 of these reactions by the NACRE collaboration [43] in 1999; a new collection of 56 charged-particle reaction rates for stable and proton-rich unstable isotopes in the mass 20 - 40 region by Iliadis et al. [44]; collections of rates derived from statistical model cross section calculations by Rauscher and Thielemann [45], Woosley and Hoffman [46], and Goriely [47]; and the REACLIB rate library [48] which includes approximately ~ 8000 reactions, most from Hauser-Feshbach statistical model calculations. Some of these collections [9,43,44,48] include rates based on evaluated cross sections. However, these rates were based on evaluations of the total cross section only, over a

limited energy range - sufficient to determine a reaction rate over temperatures appropriate for a wide range of astrophysical environments. Complete ENDF-style cross section evaluations are not necessary for this type of work. The NACRE work includes bibliographic information and cross section data from all measurements of the reactions, something missing in the Caughlan and Fowler work, and rate uncertainties (although not quoted as  $2\sigma$  limits) as well as calculated astrophysical S-factor. The Iliadis et al. work has similar features with much attention given to the rate uncertainties. In these two collections and that of Caughlan and Fowler, each rate has a different analytical form – a disadvantage when hundreds of these reactions are needed in astrophysical models. REACLIB, however, uses the same analytical form for all reactions, and therefore astrophysical models using it gain significantly in speed over the other using rate collections. One rate collection exclusively uses tabular rate values [47], while others [9,43] include both formulae and tabular values.

Other useful data sets include experimental cross sections, nuclear model calculations, evaluated cross sections, and bibliographic information. A list of data sets available (up to 1995) can be found in ref. [10]. A reference list of resources was also compiled by a steering committee [33] and posted online [49]. Compilations of unevaluated experimental cross sections of astrophysically relevant reactions are valuable, for example, because such compilations are the first step in obtaining evaluated cross sections. These compilations are also valuable for detailed studies of a particular reaction - for example, where different fits to the data are explored, where the data is fit over a different energy range, or where the data are rescaled to account for systematic uncertainties. Cross section uncertainties are needed in these compilations, since they are necessary to generate reaction rate uncertainties. The Cross Section Information Storage and Retrieval System (CSISRS) [50] at the U.S. National Nuclear Data Center (NNDC) is an online compilation of cross sections in the internationally accepted EXFOR format. This database has relatively good coverage of neutron-induced reactions, but sparse coverage for charged-particle reactions.

Furthermore, there is a strong need for evaluated cross sections for capture, transfer, exchange, and some other types of reactions occurring in astrophysical environments, since they are used to calculate reaction rates for direct input into astrophysics codes. The evaluated data sets are produced by combining a set of measurements, augmented by model results, into a cross section as a function of energy which is formatted in a standardized, well-documented manner. Access to the cross sections (as opposed to the rates) are useful for a number of reasons: for calculating reaction rates over a non-standard temperature range; for generating astrophysical S-factors; for examining the extrapolation of S-factors to unmeasured energy ranges; and for examining the quality of particular evaluations. Cross section uncertainties are also necessary because of their usefulness in determining reaction rate uncertainties. As mentioned above, ENDF [51] and similar general purpose evaluated cross section libraries [10] contain, in general, more information than is needed for the determination of thermonuclear reactions in astrophysics.

## **6 Nuclear Astrophysics Data Projects**

A number of projects to address current deficiencies in existing charged-particle nuclear data sets for nuclear astrophysics are discussed below.

### **6.1 Explosive Hydrogen Burning Reaction Evaluations**

It is very important to evaluate the rates along the proton dripline for the Hot CNO cycle and the beginning of the rp-process ( $A < 20$ ), combining indirect and direct measurement information. These reactions are important for diagnosing observations of nova explosions and X-ray bursts, and are not contained in the Caughlan and

Fowler, NACRE, or Iliadis et al. rate collections. The REACLIB rates for these reactions are, in many cases, quite old and desperately need updating. This project was given a high priority by a steering committee [33].

## **6.2 Expanding the Caughlan and Fowler Rate Collection**

While 86 of the 160 rates in the Caughlan and Fowler collection [9] were updated by the NACRE collaboration [43], there is a strong need to update the other approximately 80 rates which are now 12 years or more out of date. Since these rates are used in studies of a wide range of astrophysical phenomena, this project would have a wide impact on the field.

## **6.3. Selectively Modifying Rates in the NACRE Collection**

Some rates in the Caughlan and Fowler collection [9] updated by the NACRE collaboration [43] are still preferred by some because they were based on both direct and indirect information. Other rates in the NACRE collection use polynomial fits to S-factors rather than R-matrix fits, which may be more appropriate in some cases. Finally, the NACRE rates use parameterization different from that in the REACLIB or Caughlan and Fowler collections. The parameterizations of the NACRE rates using the REACLIB format would be very useful, as would a very selective updating of some NACRE rates to include R-matrix fits of experimental data and indirect reaction information (e.g., transfer reaction measurements) when necessary.

## **6.4 Heavy Radioisotope Production Reaction Evaluations**

The Iliadis et al. rate collection [44] almost fully addresses one of the high priority items cited by a steering committee [33]. However, it may be very useful to selectively extend this type of work to mass 40 - 60, to cover reactions important in the synthesis of long-lived radioisotopes  $^{44}\text{Ti}$  and  $^{60}\text{Fe}$  that play a role in diagnosing supernova explosions. While some reactions in this mass range are amenable to a statistical model treatment, others are dominated by individual resonances and need to be treated on an individual basis. Also, a determination of the uncertainties of some of these rates, in the manner done by Iliadis et al., would be very valuable.

## **6.5 Inhomogeneous Big Bang Nucleosynthesis Reaction Evaluations**

As discussed in Section 4.1, there is renewed interest in IBBN models because of the latest observations in cosmology. Data from the MAXIMA and BOOMERANG devices is still being analyzed, and the MAP platform will be launched soon – all of which promises more information on the early Universe and may give even more motivation to study IBBN models. However, the rates for IBBN reactions have never been thoroughly evaluated, and this should be done to enable the best prediction of element synthesis in the early Universe when the assumption of a homogeneous composition is dropped.

## **6.6 Supermassive Star Reaction Evaluations**

As discussed in Section 4.5., there is renewed interest in the evolution of supermassive stars, because of recent observations and because some of these reactions are now addressable with beams of radioactive isotopes. The last evaluation of supermassive star reactions was in 1989 [42], and a new evaluation of some of these reactions (e.g., those involving  $^{11}\text{C}$ ) may be very useful.

## **6.7 Modifying the REACLIB Collection**

REACLIB includes approximately ~ 8000 reactions, most from Hauser-Feshbach statistical model calculations. Because REACLIB uses the same analytical form for all reactions, astrophysical models using it gain significantly in speed over those using rate collections with different parameterizations for each reaction (e.g., NACRE, Caughlan and Fowler). REACLIB is a very valuable and extensive collection of rates for astrophysics studies [48]. There are, however, some features that could be improved. For example, there is little information about the source of the rates, there is no uncertainty information on the rates, and no cross section or S-factor information is compiled. Additionally, the latest Hauser-Feshbach statistical model calculations [45] need to be incorporated into REACLIB, as do the NACRE rates and those from the new Iliadis et al. collection. An important long-term project is therefore to address these shortcomings of the REACLIB collection.

## **6.8 Expanding the CSISRS Cross Section Compilation**

The CSISRS database [50] has relatively good coverage of neutron-induced reactions, but sparse coverage for charged-particle reactions. It has, however, been significantly updated in recent years with additional charged-particle reactions, most notably those in the NACRE collection, by an effort at the NNDC. Continued updating of the CSISRS database with charged-particle reactions is very important for the field.

## **6.9 The ENDF Evaluated Cross Section Database**

As discussed above, full ENDF-style evaluations are generally not needed for astrophysics studies, however; only evaluations sufficient to determine thermonuclear reaction rates are necessary. Therefore, updating ENDF and similar evaluated cross section databases is not a high priority for nuclear astrophysics. However, whenever cross sections are evaluated (in a less extensive manner), they should be put in an ENDF-compatible format so that full evaluations can be pursued at a later date if warranted.

## **6.10 Dissemination Projects**

There are a number of dissemination projects that would be very beneficial for nuclear astrophysics; many of these are detailed in Appendix 1 of ref. [10]. One of the most important is the establishment of a central archive for specialized sets of nuclear data for astrophysics models that would be accessible via the World Wide Web.

## **7 Summary**

Progress in understanding a diverse range of astrophysical phenomena - such as the Big Bang, the Sun, red giant stars, massive star evolution, and stellar explosions - can be significantly aided by improved compilation, evaluation, and dissemination of charged-particle reactions. The charged-particle reaction data needs in these and other astrophysical scenarios is summarized, and some of the existing nuclear data sets for nuclear astrophysics are described. A number of projects to address current deficiencies in these data sets are described, including: evaluating reactions for explosive hydrogen burning, supermassive star evolution, inhomogeneous big bang nucleosynthesis, and the production of heavy radioisotopes in stellar explosions; expanding and / or modifying the CSISRS cross section compilation and NACRE and REACLIB reaction rate collections, and dissemination projects such as establishing a central archive for specialized sets of nuclear data for astrophysics models.

## Acknowledgements

ORNL is managed by UT-Battelle LLC for the U.S. Department of Energy under contract DE-AC05-00OR22725. Gerry Hale, Victoria McLane, Eric Norman, Donald Smith, Roger White, and Stan Woosley contributed to Sections 1 & 2. Thanks to Rob Hoffman, Stephane Goriely, Franz Kaeppeler, Rob Cavallo, and Jeff Blackmon for useful discussions.

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