Prior to measuring the 65.5-keV resonance, the performance of our detector system will be evaluated using well-known resonances in ^{17}O(p,α)^{14}N (E_p^{cm} = 193 keV, $\omega\gamma$ = 1.66 meV [New07]) and ^{18}O(p,α)^{15}N (E_p^{cm} = 150.8 keV, $\omega\gamma$ = 0.167 eV [LW79, Ili10b]). These resonances are a factor of 3.5×10^5 and 3.5×10^7 times stronger than the resonance of interest, respectively and thus can be measured quickly and with high precision. These measurements will form part of the thesis work of UNC graduate student Clay Wegner.

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2.3.4 Investigating Rubidium Production in AGB Stars at the High Intensity γ-ray Source

Project Abstract:

Scientific Objectives: Rubidium elemental abundance measurements in massive AGB stars can place a strong constraint on conditions deep within the star. A high neutron flux is thought to produce ^{87}Rb, but the nuclear reaction-rate uncertainties are currently not well-enough known to make robust theoretical predictions on the quantity.

Method: The ^{87}Rb(γ,γ')^{87}Rb and ^{87}Rb(γ,n)^{87}Rb reaction cross sections will be measured at HIγS. Level energies, level densities, and neutron and γ-ray partial widths will be determined. These will be used as ingredients for Hauser-feshbach theoretical cross sections.

Science Impact: The reaction rate uncertainty will be reduced significantly from its current factor of 10. These measurements will place strong constraints on rubidium production in massive AGB stars.

Personnel:

TUNL Faculty: R. Longland(20%), R.V.F. Janssens
Graduate Students: William Fox
Postdocs/Research Scientists:
Collaborators:

Facilities: HIγS
Major Resources: N/A
Other Funding: Funded through DOE Early Career Award Number DE-SC0017799.

1. Scientific Motivation

Neutron capture processes are responsible for the nucleosynthesis of almost every element heavier than iron in the cosmos. These processes can be divided into two broad categories: the r-process, which occurs during Type II supernovae and neutron star merging events; and the s-process, which occurs in massive stars and Asymptotic Giant Branch (AGB) stars. The r-process describes the rapid capture of neutrons so the nucleosynthesis path is far from the stable isotopes. The s-process, on the other hand, involves neutron captures that are typically slower than the rate of β decay. In this case, nucleosynthesis follows the valley of stability. Each one of these processes is responsible for producing about 50% of the elements, though the detailed picture is more complicated. For example, some isotopes are shielded from the r-process (see Ref. [Kae82]), and thus can only be produced by the slow neutron capture process. The abundances of these s-only isotopes provide stringent constraints on chemical evolution models.

Individual stars can also exhibit very different abundance patterns that indicate the operation of the s-process. These stars are ideal stellar laboratories with which to test stellar models. For example, some massive AGB stars in our galaxy have been shown to exhibit a large overproduction of rubidium with respect to solar abundances [GH06, Gar07]. This overproduction occurs when the neutron flux becomes high enough for neutron capture to occur faster than β-decay for some isotopes. This creates a "branching" in the s-process path. Examples of these branchings are at ^{85}Kr and ^{86}Rb. If the neutron flux becomes high enough to activate these branchings, the ^{87}Rb abundance will become elevated. However, detection of elevated rubidium in massive AGB stars is only a powerful diagnostic tool if the nuclear cross sections are well known.

Shortly after the detection of an overabundance of rubidium in massive AGB stars, Ref. [Lug08] highlighted the ^{86}Rb(n,γ)^{76}Rb as one of the most important reactions that must be further constrained in order to help improve model predictions. ^{86}Rb is unstable, so a direct determination of that cross section is unfeasible. However, it can be well constrained by determining the nuclear structure of ^{87}Rb. Here, we propose a measurement of the ^{87}Rb(γ,γ')^{87}Rb and ^{87}Rb(γ,n)^{86}Rb cross sections, which will significantly constrain the reaction rate, and provide a powerful tool to compare AGB star models with observations.

2. Accomplishments During the Last Grant Period

We have already begun performing sophisticated nucleosynthesis calculations to further motivate this project. Those can be seen in Fig. 2.3–14 for the case of the ^{87}Rb(n,γ)^{88}Rb reaction. Clearly, in this case, as the reaction rate is increased *within its uncertainties*, more ^{87}Rb is destroyed. We have similar calculations for ^{86}Rb(n,γ)^{87}Rb, which is the reaction of interest to us, but more work is underway to more closely match the stellar burning conditions expected in AGB stars, and to ensure that the ^{87}Rb production is being appropriately quantified. The advances we have made so far provide strong motivation for the HIγS experiment, but also contribute significantly to developing the ancillary tools for Starlib. These techniques will enable us to more efficiently identify reactions that should be measured both at TUNL or at FRIB in the future.

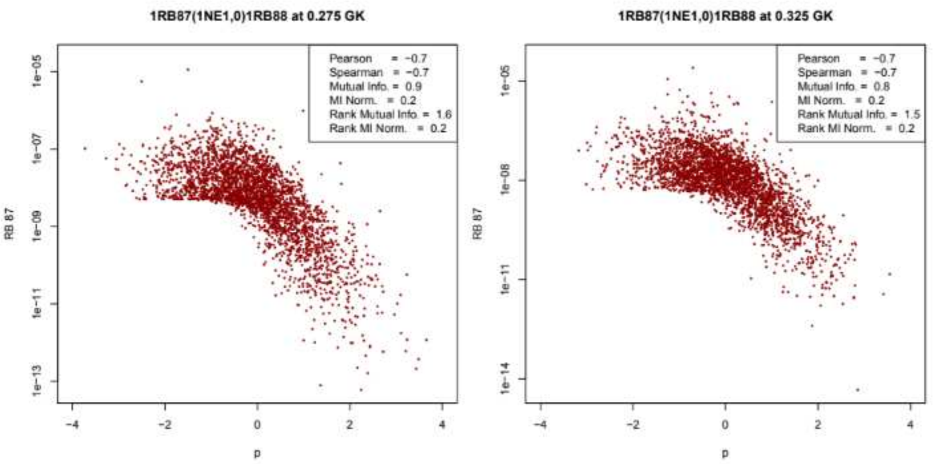

Figure 2.3–14: Results of a Monte Carlo nucleosynthesis calculation that show the effect of uncertainties in the ^{87}Rb(n,γ)^{88}Rb on ^{87}Rb production in AGB star conditions.

We are also already working on upgrading the data acquisition system for the existing detector system at HIγS. This system, based on CAEN V1730 digitizers and the data acquisition system MIDAS [Rit99], will provide us with a consistent data collection and analysis framework for all of our experiments at TUNL. The user-code for the DAQ was recently completed and is now undergoing rigorous testing. We are developing and testing drivers for the V1730 digitizer at present, which is expected to be completed by the Fall of 2020.

3. Project Description

To constrain the neutron capture cross section on ^{86}Rb, we will perform nuclear resonance fluorescence experiments on ^{87}Rb to determine the nuclear structure of the compound nucleus. These constraints will allow rubidium abundances in massive AGB stars to be used as a diagnostic of stellar models.

Current efforts are underway to improve or normalize beam flux monitoring methods using a ^{238}U fission chamber such as that described in Ref. [Wen93]. We will collaborate with W. Tornow and C. Howell to integrate the fission chamber into the data acquisition system. We will cross-calibrate the fission chamber with high-efficiency NaI(Tl) detectors that are known to accurately measure low beam intensities. Once the fission cross section is normalized at low intensities, it will provide a robust, live beam current monitoring system to HIγS. Once complete, we plan to perform a systematic study of the various flux monitoring techniques at use at HIγS. This study will ensure the accuracy of future photon-induced reaction cross section measurements.

At HIγS, the ^{87}Rb(γ,γ')^{87}Rb reaction will be measured using the new HPGe Clover array for Nuclear Resonance Fluorescence (NRF) developed by R.V.F. Janssens as detailed in Sec. 2.2.6. The setup will be used to measure the γ-ray strength function in ^{87}Rb over a broad range of energies both below and above the neutron threshold. The strategy we will employ follows that outlined in Refs. [Rau13, Sch13]: Below the neutron threshold, the new NRF will be used to accurately map out the γ-ray strength function. Above the threshold, neutron branches will be measured using the 4π neutron detector detailed in Ref. [Arn11]. Combined, these measurements will not uniquely determine the ^{86}Rb(n,γ)^{87}Rb cross section, but they will give us critical information to constrain the cross section sufficiently to understand rubidium production in massive AGB stars. We will collaborate with theoretical nuclear physicists to improve Hauser-Feshbach estimates of the reaction rate. Our flexible data electronics developed for the Enge Split-pole Spectrograph will be leveraged to make these measurements possible.

Following the experimental results, we will perform more sophisticated stellar modelling to detail the effect this cross section has on the nucleosynthesis of rubidium in massive AGB stars. A full multi-zone astrophysical model is required to calculate quantifiable surface abundances, as opposed to the simplified single-zone model used above to identify this reaction as important. We have started building AGB star models in MESA to begin this work, but will collaborate with experts at Monash University in Melbourne, Australia to perform the final nucleosynthesis models. The end result of this project will be accurate, experimentally determined rubidium production cross sections for use in stellar models. These will provide a stringent constraint on mixing processes in massive AGB stars to explain elemental abundance observations. This project is the thesis work of graduate student William Fox.

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2.3.5 Constraining Nitrogen Isotopic Ratios in Core-collapse Supernovae

Project Abstract:

Scientific Objectives: Nitrogen isotopic ratios in matter ejected from supernova explosions provide a stringent constraint on the strength of the shockwave as it passes through the outer shells of an exploding star. Many of the reactions that determine the nucleosynthesis of ^{15}N, however, are poorly known.

Method: The reactions ^{18}F(n,α)^{15}N and ^{18}F(n,p)^{18}O have been shown to be critical in predicting ^{15}N production in the shocked helium shell of an exploding massive star. We will measure excitation energies, spin-parities, and particle decay branching ratios of ^{19}F at the high excitation energies relevant to ^{18}F+n.

Science Impact: Improved ^{15}N nucleosynthesis predictions for material ejected from supernovae. We estimate that our new measurements will reduce the ^{18}F+n reaction rate uncertainties by a factor of 20.

Personnel:

TUNL Faculty: R. Longland(35%), A.E. Champagne, C. Iliadis, R.V.F. Janssens, A.D. Ayangeakaa
Graduate Students:
Postdocs/Research Scientists: Postdoc to be hired in 2021
Collaborators:

Facilities: Tandem Accelerator
Major Resources: Enge Split-pole Spectrograph, Ion Implanter
Other Funding:

1. Scientific Motivation

Core collapse supernovae are violent deaths of massive stars. As these stars evolve quiescently, they proceed through a sequence of burning phases that, over the course of their life, convert hydrogen into iron in their cores. The structure of these stars following this evolution resembles that of an onion, with stratified layers of heavier elements towards an electron-degenerate iron core. Nuclear burning continues at the interface between those shells, gradually adding mass to the core until it becomes unstable to gravitational collapse. The subsequent core bounce generates copious amounts of neutrinos and a shock-wave that travels outward through the shells of the star. The observational counterparts of these events are Type II supernova. These explosions are responsible for producing a large fraction of elements heavier than iron in our solar system. However, the physics that drives supernovae and their role in the origin of the heavy elements is not well understood.

Microscopic grains of dust from supernovae can become embedded into meteorites that eventually make their way to earth. Careful isolation and isotopic analysis of these grains then provides us with pristine isotopic abundance ratios from individual exploding stars [Nit14]. Of particular interest are isotopic abundance ratios, which can show strong deviations of orders of magnitude from the nearly constant ratios found elsewhere in the solar system. Not only can these ratios provide us with important information regarding the grains' origin, but can help us constrain stellar models. Unlike observational astronomy, which provides elemental abundances with large uncertainties, presolar grain analysis can provide precise isotopic abundance ratios. Figure 2.3–15 is an example of isotopic abundance ratio measurements, where nitrogen ratios are plotted against carbon ratios for a large number of SiC grains.

Nitrogen isotopic ratios are a key indicator for the supernova paternity of a given presolar grain: ^{15}N is produced in the helium shell of an exploding star as the shockwave passes through it. However, the nuclear reaction rates affecting the nucleosynthesis are uncertain [Boj14, Pig15]. Specifically, those studies found that the nucleosynthesis of ^{15}N is governed by the rates of the ^{18}O(α,n)^{21}Ne, ^{18}F(n,α)^{15}N, ^{18}F(n,p)^{18}O, and ^{15}N(α,γ)^{19}F reactions. Recent measurements [Bes13] have improved the experimental information for the ^{18}O(α,n)^{21}Ne reaction, but the impact of that study on the nucleosynthesis predictions have not been fully investigated.

Direct laboratory measurements of the ^{18}F(n,α)^{15}N and ^{18}F(n,p)^{18}O reactions are challenging since as they involve both a radioactive target and a radioactive beam. Radioactive beam measurements at FRIB, for example, would, therefore, be almost impossible at this time; hence a nuclear structure measurement is needed. The inverse reactions in this case are also unhelpful because

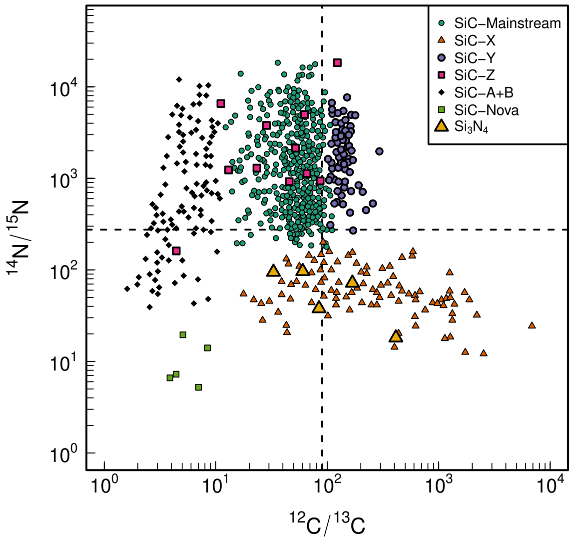

Figure 2.3–15: Nitrogen abundance ratios plotted against carbon ratios for a collection of presolar SiC grains [Hyn09]. A number of distinct groups can be clearly identified, with the "SiC-X" grains being predicted to originate in Type-II supernovae.

the α-particle and proton decay will preferentially populate excited states, so the reciprocity theorem would not be applicable. We will employ novel methods to extract the key nuclear structure information required to constrain the cross sections of the ^{18}F(n,α)^{15}N and ^{18}F(n,p)^{18}O reactions.

2. Accomplishments During the Last Grant Period

To investigate the findings of Bojazi and Meyer [Boj14] in more detail, we extracted a single-zone temperature-density evolution from their models. All of the nucleosynthesis occurs within just a few seconds. The post-explosion evolution of ^{18}F and ^{18}O is due to β-decay of ^{18}F with $T_{1/2} = 110$ minutes. The reaction rates used here are the standard set adopted from `Starlib` [Sal13].

The `Starlib` reaction rate library allows us to vary the rates *within their uncertainties* (either experimental or theoretical) using Monte Carlo techniques. This method was explored in detail in Ref. [Lon12]. By plotting the isotopic abundance of interest against the Monte Carlo rate variation parameter, p_i, one can identify the reactions whose rate uncertainties most impact the production of that isotope. A few examples of reactions that affect the abundance of ^{15}N are shown in Fig. 2.3–16. Take the ^{18}F(n,p)^{21}Ne reaction, for example, which is displayed in the center panel of Fig. 2.3–16. The vertical line at zero corresponds to the recommended rate for this reaction, which is taken from the Hauser-Feshbach reaction rates of Cowen *et al.* [Cow91] with an assumed theoretical uncertainty of a factor of 10. The figure shows that if this rate is reduced, it doesn't impact the synthesis of ^{15}N significantly (the points are randomly scattered). However, if this rate is *increased*, the synthesis of ^{15}N is decreased dramatically. This reaction and the competing ^{18}F(n,α)^{15}N reactions should be measured.

Importantly, we have also investigated the reaction rate *precision* required to constrain the temperature of the shock when it passes through the helium layer. We find that when reaction rate uncertainties are included, the predicted uncertainty in ^{15}N production increases by a factor of two. In the following, we propose experiments aimed at reducing the uncertainty of the ^{18}F(n,α)^{15}N,

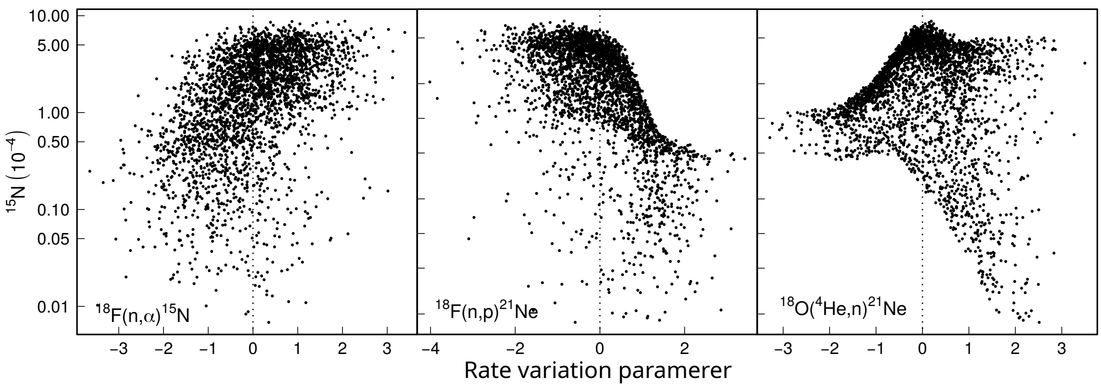

Figure 2.3–16: Monte Carlo correlation plots for three key reactions. The x-axis corresponds to variation factors within the reaction's current uncertainties. In this case the uncertainties are assumed to be a factor of 10. These variation values are described in the text and in Ref. [Lon12]

^{18}F(n,p)^{18}O, and ^{15}N(α,γ)^{19}F reactions from a factor of 10 to approximately 50%. This will significantly improve the predictive power of the nucleosynthesis models. Our findings may indicate the need for future work if this improvement is insufficient. However, we will identify precisely which energy ranges must be measured. These findings will provide strong guidance for future measurements.

3. Project Description

We showed that the ^{18}F(n,α)^{15}N and ^{18}F(n,p)^{18}O reactions strongly affect ^{15}N production in supernovae. The former directly produces it, while the latter provides protons for the subsequent ^{18}O(p,α)^{15}N reaction. Both of these reactions proceed through excited states in ^{19}F, with a neutron separation energy of $S_n = 10.431$ MeV [Aud03]. The α-particle and proton separation energies are $S_\alpha = 4.014$ MeV and $S_p = 7.994$ MeV, respectively.

^{18}F is radioactive with a half life of $T_{1/2} = 110$ minutes. Therefore, we cannot perform direct reaction measurements of the ^{18}F+n cross sections. Instead, we turn to high resolution particle transfer reactions using stable targets of ^{18}O. By performing ^{18}O(^{3}He,d)^{19}F proton transfer measurements, we can populate the same states in ^{19}F as those populated in the ^{18}F(n,α)^{15}N and ^{18}F(n,p)^{18}O reactions of interest. We can determine several important nuclear properties this way: (i) the energies of excited states in ^{19}F, (ii) the spins and parities of those states, and (iii) their particle-decay branching ratios using particle detectors close to the target. These measurements will be performed at the TUNL Enge Split-pole Spectrograph.

The proton transfer reaction will be used to populate the levels of interest at $E_x = 10.4$ MeV using a 21 MeV ^{3}He beam. A new ^{3}He gas re-circulation system was recently installed at TUNL and has been successfully used in several experiments (Refs. [Set18, Set19, Ham20] and others undergoing analysis). The targets will be produced by implanting ^{18}O into carbon foils using the TUNL ion implanter, which is used exclusively by the TUNL astrophysics group for target preparation.

Performing the ^{18}O(^{3}He,d)^{19}F particle transfer experiment at the TUNL Enge Split-pole spectrograph requires a magnetic field of approximately 9.4 kG for a 21 MeV ^{3}He beam. The resolution of our focal plane detector was recently investigated thoroughly [Mar19] and found to be $\Delta\rho = 0.03$ cm. This corresponds to about 12 keV for this magnetic field. Since the average level spacing in

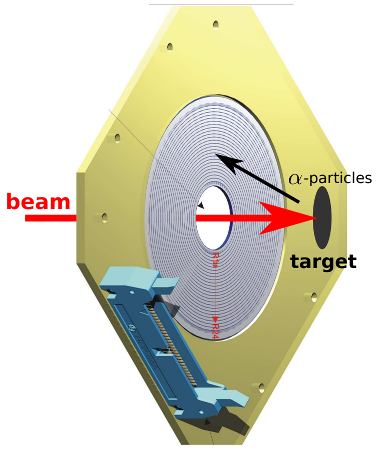

Figure 2.3–17: Illustration of the geometry to measure particle decays of levels populated in the ^{18}O(^{3}He,d)^{19}F reaction.

this excitation energy region is about 40 keV [Til95], we expect to resolve most states.

Another important nuclear physics property required to constrain the reaction rates are the branching ratios for the various particle-decay modes. For the ^{18}F(n,α)^{15}N and ^{18}F(n,p)^{18}O reactions of interest here, the α-particle and proton branches are essential for understanding nucleosynthesis of ^{15}N. To perform particle coincidence measurements, we require position sensitive silicon detectors that will be placed inside the target chamber. We therefore request funds to purchase two double-sided silicon strip detectors and their associated electronics. Two "S3" detectors (E and ΔE) from Micron Semiconductor are required to measure energy and position of decay particles at backward angles. These experiments will be performed *in coincidence* with particle detection on the focalplane. For example, deuterons from the ^{18}O(^{3}He,d)^{19}F reaction will be detected on the focal plane, which will be used as coincidence requirements for particles arriving at the silicon detector. Typically, such measurements require very low beam currents to avoid damaging the silicon detectors by particle scattering, particularly from the beam stop. However, the TUNL spectrograph contains a inter-pole beam stop. It is located far away from the reaction chamber and can be positioned to prevent high-intensity beam particles from damaging the focalplane detector. In contrast, this type of measurement would be unfeasible at other split-pole spectrograph facilities using high-current beams. This project will also be a major upgrade to the capabilities of the TUNL nuclear astrophysics program. This project will be led by a postdoctoral researcher to be hired in 2021.

4. Budget: $50,000

The silicon detectors requested amount to one ΔE 65 μm and one 1000 μm S2/S3-type detector from Micron Semiconductors Ltd. The cost of these detectors is $16,875, based on a recent quote from the manufacturer. In addition, readout electronics is required for the silicon detectors. The amount requested represents two 16-channel digitizers ($16,380 total) and a VME crate ($8,567) required to house them locally in the Enge Split-pole Spectrograph target area, as well as the other VME readout electronics already on hand. These digitizers, Mesytec MADCs, remove the need for additional signal readout electronics by processing raw signals using FPGA firmware. They also provide synergy with the digitizer technology used by the nuclear structure and LENA groups. The amount reflects a quote obtained from Weiner, the US dealer of these products.

Funds are also requested for electronics, cables, and preamplifier modules ($5,000), machine shop services ($1,433), and other miscellaneous hardware such as stepper motors, tools, mounting structure material, etc. ($1,745). These estimates are based on recent experience.

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2.3.6 STARLIB: A State-Of-The-Art Library of Thermonuclear Reaction Rates

Project Abstract:

Scientific Objectives: Maintaining and improving STARLIB, a state-of-the-art library of thermonuclear reaction rates.
Method: Monte Carlo and Bayesian computation of thermonuclear reaction rates, and use of the computed rate probabilities in Monte Carlo reaction network studies.
Science Impact: STARLIB will significantly improve nucleosynthesis predictions because, unlike other existing libraries, it provides reaction rate probability densities and statistically meaningful rate uncertainties. This information is a prerequisite for performing realistic nucleosynthesis studies.

Personnel:

TUNL Faculty: C. Iliadis(30%), R. Longland(5%)
Graduate Students: David Gribble, Caleb Marshall
Postdocs/Research Scientists: none
Collaborators: Alain Coc (Orsay), Jordi Jose (Barcelona), John Lattanzio (Monash University), Nicolas de Séréville (Orsay)

Facilities: No experimental facilities needed.
Major Resources: Existing computer server "starlib"
Other Funding: none

1. Scientific Motivation

The thermonuclear rate evaluations published by Fowler and collaborators at regular time intervals were game-changing for the field of nuclear astrophysics. They represented the best information available and provided a common foundation to rest stellar models on. Their last paper was published in 1988 [Cau88]. Although several other evaluations were published over the next two decades [Ang99, Ili01], the methods employed to estimate thermonuclear reaction rates were essentially identical to those pioneered in the earlier work.

TUNL led the way towards a paradigm shift. In 2010, we published a series of four papers [Lon10, Ili10c, Ili10a, Ili10b] that laid the foundation for estimating statistically sound thermonuclear reaction rates based on Monte Carlo sampling of the experimental nuclear physics input. This new method, which has now been widely adopted in our field, does not only provide rigorous rate uncertainties, but gives the full rate probability densities at all desired temperatures. This information, in turn, is crucial for performing realistic nucleosynthesis studies using reaction networks. Experimental Monte Carlo-based reaction rates are now available for about 100 nuclear reactions in the target mass region of $A = 2 \smile 40$. These rates form the backbone of the rate library STARLIB, which was developed at TUNL in 2013.[1] It contains recommended rate values, rate uncertainties, and rate probability densities. For more information, see Ref. [Sal13].

In recent years, TUNL has again taken leadership in this area by applying Bayesian techniques [Ili16] to the analysis of reaction cross section data that were not amenable to the application of the Monte Carlo method mentioned above. This development will be discussed in more detail below.

2. Accomplishments During the Last Grant Period

During the last grant period, we have implemented a number of new experimental Monte Carlo-based reaction rates into STARLIB. Examples are ^{22}Ne(p,γ)^{23}Na and ^{30}Si(p,γ)^{31}P important for globular clusters, ^{29}Si(p,γ)^{30}P of interest to presolar grains, and a host of key reactions for big bang nucleosynthesis (see below). We have recently used STARLIB to study the nucleosynthesis of presolar grains [Ili18]. The library was also used in a study of galactic ^{7}Li production and supernova Ia progenitors [Sta20], which was prominently featured in Forbes magazine[2].

The Monte Carlo reaction rate method was extended in the last grant period to include correlations between resonance parameters. In many cases, resonance strengths or partial widths are measured in a single experiment and are normalized to a single reference resonance. This normalization procedure produces correlated uncertainties. We investigated the effect of these correlations on reaction rates, finding significant effects when several resonances contribute to the reaction rate [Lon17]. This is highlighted in Fig. 2.3–18, where the isotopic abundance ratio ^{26}Al/^{27}Al at the end of C/Ne convective shell burning in massive stars becomes more uncertain when correlations in ^{23}Na(α,p)^{26}Mg resonance strengths are taken into account. More recently, we investigated the effect of correlated resonance energies on reaction rate uncertainties. In this case, we found the effects were more difficult to predict. A paper describing these findings was recently accepted to Astronomy and Astrophysics.

Our most significant recent achievement for the estimation of reaction rates, has been the development of a Bayesian method to analyze nuclear cross section data. The strength of a hierarchical

[1] STARLIB is publicly available at `https://starlib.github.io/Rate-Library/`.

[2] `https://www.forbes.com/sites/startswithabang/2020/06/03/lithium-mystery-solved-its-exploding-stars-not-the-big-bang-or-cosmic-rays/#543370264118`.