Experimental Needs and Opportunities in Nuclear Astrophysics

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Abstract. Nuclear Astrophysics is a wide field covering the nuclear physics basis of nucleosynthesis and energy generation processes in quiescent and explosive stellar burning environments. This presentation will focus on the experimental basis of key reactions in different phases of quiescent stellar burning, discussing the experimental and theoretical basis of presently adopted reaction rates. New experimental facilities are being planned and implemented and may provide important information for reducing the overall uncertainties of these rates which will improve the simulations of late stellar evolution providing an improved basis for predicting the seed material for subsequent explosive processes.

1. Nuclear reactions in stars
Nuclear Astrophysics is concerned with nuclear processes in all stellar environments. The first scientific goal of the field is the study of the chemical evolution of the Universe starting with the first minute of the Big Bang after the decoupling of the weak forces. The build-up of the presently observed elements from the original proton neutron abundance in the early Big Bang universe occurred through complex nuclear reaction chains starting from the first generation of stars with primordial abundance distribution, building the presently observed elemental and isotopic abundances through many generations of stars. This evolution was summarized by Carl Sagan in his famous expression “We are star stuff” and is visualized in figure 1.

Figure 1: Evolution of the isotopic abundance distribution in our universe; (1) primordial abundances predicted from standard Big Bang theory; (2) abundance distribution observed in early stars; (3) solar abundance distribution as observed today.
A particularly significant role of Nuclear Astrophysics is concerned with the identification of new nuclear physics based signatures to probe the nuclear processes that are taking place in the deeper cores of stars not accessible through traditional astronomical techniques. This ranges from the observation of neutrinos from our sun and near-by supernovae through neutrino detectors located in deep underground locations, to satellite based gamma ray detectors mapping the distribution of radioactive elements in our galaxy. Observations about the nature of the solar core from neutrino observations complement helioseismographic measurements of our sun; star quakes emerge as new important methods to probe the inner conditions of stellar burning zones in massive stars such as Betelgeuse. The sudden burst of X-rays observed from thermonuclear explosions on the surface of neutron stars can be correlated with the emergence of gravitational waves originated by these events through observation with the gravitational wave detector LIGO.

All these observations are complemented by experimental efforts where accelerators are being used to mimic the stellar reaction processes that drive the evolution of our sun and the explosion of far distant supernovae. These experiments are extremely complicated, since it takes stellar reactions billions of years to burn their fuel in stars, and only seconds to burn it in supernovae or other stellar explosions. A broad experimental portfolio has been developed to drive forward our understanding of the life and death of stars and to benchmark the ever more complex computer simulations of these events.

This paper is concerned with the development of new experimental facilities, techniques, and equipment to probe nuclear reactions of significance for addressing the above formulated questions in nuclear astrophysics. This ranges from facilities positioned deep underground to probe critical low cross section reactions that control stellar evolution to reactions at the limit of stability that provide the energy for stimulating stellar explosion. The specific needs for studying these critical reactions for stellar burning is discussed in the following sections.

2. Nuclear reactions in quiescent stellar burning

Charged particle induced radiative capture and fusion reactions are the first step in the process of the chemical evolution of our universe. From the first minutes of nucleosynthesis in the Big Bang, followed 500 million years later by the first generation of stars to the present star generation, charged particle reactions have generated the seed and the fuel for subsequently more complex nucleosynthesis processes building the elemental and isotopic abundance distribution as observed today [1]. Current stellar model simulations are at a level of precision that the nuclear reaction rates represent a major source of uncertainty for theoretical predictions and for the analysis of observational signatures. The present reaction rates are based on cross section measurements obtained at significantly higher energies than expected for the interior of stars, and are extrapolated by theoretical means towards the stellar energy range. This approach carries significant uncertainties and model dependencies that can only be reduced by measurements at significantly lower energies, which requires significantly lower background level in the detectors and significantly higher reaction yield through the increase of beam intensity.

This is demonstrated in the two examples shown in figure 2, the $^{3}\text{He} (\alpha, \gamma) ^{7}\text{Be}$ reaction, which opens the pp-II branch in the pp-chains responsible for most of the neutrino production in the sun [2] and the $^{12}\text{C} (\alpha, \gamma) ^{16}\text{O}$ reaction in stellar helium burning which is responsible for the $^{12}\text{C}/^{16}\text{O}$ ratio in our universe [3]. In both cases the reaction cross section drops exponentially towards lower energies and data are only available for the upper energy range. The Gamow window for the $^{3}\text{He} (\alpha, \gamma) ^{7}\text{Be}$ reaction in our sun is near 20 keV, while the Gamow range for the $^{12}\text{C} (\alpha, \gamma) ^{16}\text{O}$ reaction in stellar helium burning is around 300 keV. To determine the cross section and therefore the reaction rate, better low energy data and an improved reliable extrapolation compared to what is presently available is necessary. In both cases the cross section is determined by direct radiative capture contributions and tails of broad resonances or sub-threshold states as well as the interference terms between all these components. A reliable
extrapolation therefore requires a detailed understanding of the various reaction components and the way they interact with each other, something that can only be tested by experiment. Figure 2 shows the extrapolation based on the R-matrix code AZURE [4], which takes into account all available experimental channel data. The R-matrix extrapolation predicts cross sections well below femto-barn, which requires the development of new or improved experimental methods for reliable measurement, which traditionally rely on using low energy accelerators for the production of intense light ion beams on isotopically enriched target materials [5].

![Figure 2: Low energy cross section curves for the $^3$He($\alpha,\gamma$)$^7$Be reaction that opens the pp-II branch in stellar hydrogen burning and $^{12}\text{C}$(\alpha,\gamma)$^{16}\text{O}$ in stellar helium burning that determines the $^{12}\text{C}/^{16}\text{O}$ ratio in our universe. The reaction cross sections are measured at high energies and extrapolated to the stellar energy range using R-matrix theory.](image)

This challenge has been addressed by the development of two rather orthogonal techniques. The first approach relies on the enhancement of shielding surrounding the detector materials to improve the peak-background ratio. This can best be achieved by moving the accelerator into a deep underground environment as demonstrated by the successful operation and program of the LUNA facility at the Gran Sasso underground accelerator laboratory [6]. The rock shielding removes the cosmic ray induced background radiation in the detector material improving considerably the sensitivity for low energy reaction measurements. New underground facilities are being proposed and developed based on the LUNA experience, in the following I focus on the DIANA facility since it combines the advantages of underground location for decreasing the reaction background with substantial improvements in beam luminosity to increase the reaction yield.

While the traditional method relies on the use of light ion beams and the detection of light reaction products depending on solid angle and detector efficiency, inverse kinematic techniques with heavy ion beams are designed to detect the heavy ion recoils, kinematically collimated into a small forward cone and separated from the primary beam by means of magnetic and electric fields. The recoils can be detected with high efficiency with the appropriate particle detection system positioned at the focal plane of the system.

2.1. Inverse kinematics techniques with recoil separators

Recoil separators have been successfully used for the first time at Caltech for the study of the $^{12}\text{C}$(\alpha,\gamma)$^{16}\text{O}$ reaction in inverse kinematics using an intense $^{12}\text{C}$ beam on a $^4\text{He}$ gas target. The $^{16}\text{O}$ reaction products were separated by a combination of dipole and quadrupole magnets and detected by an ion chamber located at the focal plane in coincidence with the $\gamma$ signals detected by a $4\pi$ NaI gamma detection array arranged around the gas target chamber [7]. While the separating and bending
power of the magnets were limited to low mass nuclei $A<18$, this instrument, CTAG demonstrated the power of separators for low cross section experiments. The application of the recoil separator technique was developed further to utilize it for experiments with intense radioactive beams. The measurements of the $^{21}\text{Na}(p,\gamma)$ reaction at the DRAGON separator at TRIUMF [8] was the first successful application followed by recoil separator experiments at other laboratories, such as ARES at Louvain la Neuve and DRS at HRIBF in Oak Ridge. DRAGON was also used successfully for stable beam experiments [9] but the small acceptance angle kinematically limits the applications in terms of reaction $Q$-value and energy. A revised version of the CTAG, has been the ERNA separator at the Ruhr University of Bochum in Germany, which was based on CTAG components in addition to several new Wien filter elements for improving the separation and reducing the background components [10]. Both the $^3\text{He}(\alpha,\gamma)^7\text{Be}$ and the $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$ reaction have been successfully measured at higher energies, while the limitations in acceptance limited the studies of the lower energy range.

To overcome these limitations a new recoil separator, St. GEORGE has been designed at the University of Notre Dame to specifically address the challenges of low energy measurements by opening the acceptance angle and use a combination of quadrupole, dipole, and Wien filter elements for achieving optimum acceptance and separation between primary beam particles and reaction products in terms of charge, mass, and velocity of the particles [11]. The primary beam is being delivered by a newly installed 5MV Pelletron accelerator with a Nanogan ECR source positioned in the terminal for delivering high intensity heavy ion beams. The facility is completed and will focus primarily on the study of critical reactions in stellar helium burning using inverse kinematics techniques.

The target system is a recirculating $^4\text{He}$ jet gas target arrangement that allows positioning a gamma detection array close to the actual target spot. The aperture system separating the differentially pumped target stations is specifically designed to allow a wide emittance of the recoils into the separator system. Detailed tests have been performed to determine the target density distribution and to probe the target stability under high beam current conditions [12].

Figure 3 shows the design of the St. George system; the first quadrupole triplet is positioned behind the exit of the gas target system to re-focus the beam and reaction products. This is followed by the first stage of dipole magnets primarily for charge selection. The second set of dipole magnets is for q/m separation and is followed by the Wien filter which served for velocity separation between the primary beam and the reaction products along a drift distance. The final dipole quadrupole arrangement is for focusing the reaction products onto the focal plane detection system.

**Figure 3:** Design of the St. George recoil mass separator for inverse kinematics radiative capture experiments with low energy intense heavy ion beams. The gas jet target is located at the left hand side of the system; a drift stage is located after each separation stage followed by quadrupole system for refocusing the particles into the next separation section. The box located in the center of the system represents the Wien filter. The electrical and magnetic fringe fields are matched by field clamps to optimize the velocity separation between recoil products and primary beam particles.
Figure 4 shows the separation capabilities of St. George on the example of the beam-optics simulation of the $^{22}{\text{Ne}}(\alpha,\gamma)^{26}{\text{Mg}}$ reaction for two different energies. The beam bundle marked in red represents the primary $^{22}{\text{Ne}}$ beam particles; the one marked in black the separated $^{26}{\text{Mg}}$ reaction products. The simulation demonstrates the separation capabilities of the system, which is optimized for the measurement of radiative capture of alpha particles with heavy ion beams up to mass 40. Because of the large acceptance angle also nuclear reactions like $^{22}{\text{Ne}}(\alpha,\text{n})^{25}{\text{Mg}}$ can be measured because of the negative Q-value of the system which maintains the forward focusing capability of the recoil products. The system is presently being tested and benchmarked with well-known alpha capture reactions such as $^{3}{\text{He}}(\alpha,\gamma)^{7}{\text{Be}}$ and $^{14}{\text{N}}(\alpha,\gamma)^{18}{\text{F}}$. Full operation is scheduled to be started after the completion of the tests.

![Figure 4: Beam optics simulation for the $^{22}{\text{Ne}}(\alpha,\gamma)^{26}{\text{Mg}}$ reaction in the St. George separator for two energies, 472 keV and 677 keV. The red bundle marks the primary $^{22}{\text{Ne}}$ beam which is well separated from the secondary $^{26}{\text{Mg}}$ recoil products.](image)

2.2. DIANA as future US underground accelerator facility

The success of the LUNA facility led to the development of an improved accelerator laboratory, the Dual Ion Accelerator for Nuclear Astrophysics (DIANA), which covers a broader energy and luminosity range than the present LUNA facility. DIANA would consist of two high-current accelerators, a 30 to 400 kV variable, high-voltage platform, and a second, Pelletron type accelerator with a voltage range of 350 kV to 3 MV as shown in figure 5 below.

Both machines rely on classical low energy accelerator principles but are designed to generate and maintain very high beam currents from the ECR source by reducing space charge effects both in the acceleration tube system as well as in the beam optical arrangements. The low energy machine is designed for high beam currents with optimized acceleration and ion-optical focusing system [13] to minimize as much as possible space charge effects that can cause beam widening and loss of beam intensity in the entrance apertures of the gas-jet and the beam-stop target systems. The Pelletron system has an optimized ECR source ion injection system to maximize beam injection and transmission through the acceleration tube. To achieve high beam currents the design utilizes an up-charge system based on running ten chains. Compared to current astrophysics facilities, DIANA could increase the available beam densities on target by several orders of magnitudes: up to 100 mA on the low energy accelerator and several mA on the high energy accelerator. The actual beam intensity, however, will be limited by the target stability under high power beam conditions. This increases the luminosity significantly compared to LUNA and allows pursuing the experiments to much lower...
energies. The major challenge will be the production of beam induced background on target impurities. Other challenges for high luminosity experiments are maintaining the target stability for the very long period of time necessary for low cross section measurements. This requires special effort in target development both on the solid beam-stop target as well as on the gas target side. The stability of the solid target is handicapped by the change of stoichiometry through hydrogen or helium implantation. This will be reduced by maintaining the target at high temperature by cooling with hot fast flowing liquids to increase the diffusion and evaporation probability of the hydrogen and helium ions. New gas target designs are presently being tested and indicate high stability of a gas jet under intense beam bombardment.

Even in a deep underground location, residual background will handicap the detection of the weak signals of the characteristic gamma or neutron radiation from the reactions to be investigated. The rock shielding removes only the cosmic ray induced background radiation in the detector material. Yet, the background radiation component from the natural decay chains from actinides in the rock material is not removed and causes a substantial gamma background level below 3 MeV. This background has to be shielded locally. The main handicap in these kinds of experiments, however, are beam induced background components, resulting from reactions between the incoming beam particles and low Z target contaminations - such as deuterium or boron - or contamination of nearby located slit or collimator materials. This kind of background has to be removed by active coincidence shielding techniques using a combination of high resolution Ge-detectors for identifying and counting specific transition populated in the radiative capture reactions and a high efficiency summing detector for Q-value gating.

The DIANA facility is being designed as a collaborative effort by a number of university and national laboratory groups and will be operated as user facility for the experimental nuclear astrophysics community.

Figure 5: Concept for the DIANA dual accelerator facility located at an underground laboratory for nuclear and particle astrophysics research in the US. The lower energy range is covered by using a 400 KV platform with an high intensity ECR source. Higher energy beams are being produced by a new designed 3 MV Pelletron accelerator system.
2.3. Limitations and Alternatives

DIANA will significantly expand the present range of nuclear astrophysics experiments with stable beams and reduce the uncertainties in the theoretical extrapolation of laboratory data towards the stellar energy range. However, in cases of capture reaction at high Z-nuclei or other reactions with particularly low cross sections, the measurements are extremely challenging and the experiments may not be sensitive enough. In this case indirect measurements may remain the only tool to identify low energy reaction components by studying the associated nuclear structure or transition strengths components. It has been shown that the most efficient method is the use of single particle or cluster transfer or scattering reactions that can be performed at tandem or low energy cyclotron facilities at relative limited expense. These studies are not only important for the study of the low energy reactions with stable beams but do play also an important role in identifying the components of radioactive beam induced reactions, namely for the identification of resonance structure and resonance parameters in critical compound nuclei of these processes. It is safe to say that these indirect studies have contributed enormously to the field and have in many cases revealed structures not yet accessible to the direct experimental approach. Yet, the reaction predictions based on these indirect data are handicapped by the dependence on nuclear structure and reaction models necessary to translate the data into reaction cross sections and reaction rates. New efforts are necessary to improve the underlying theoretical methods in particular in reaction theory to overcome these problems.

3. Nuclear reactions in explosive stellar burning

While stellar reactions are being pursued with ever increasing accuracy at laboratories deep underground, another frontier is the study of nuclear processes that drive stellar explosions. These explosions occur on a rapid timescale of a few seconds. Radioactive nuclei formed in the explosion cannot decay within this short period of time and become part of the sequence of nuclear reactions that take place far outside the limits of stability. A study of these reactions and the nuclei along the reaction path will provide new insight in the nature of these processes, the rapid timescale of the explosion, and the associated energy release and nucleosynthesis. Experimental data will allow identifying the specific nature of the nuclear reaction pattern during the explosive event and in turn provide in comparison with the emerging abundance distribution specific data about the site and the site conditions during the explosion. The US nuclear astrophysics community therefore plays an important role in the development of FRIB as a premier machine for probing the nuclear physics associated with explosive processes situated far off the limits of stability. In the following the focus is primarily on the charged particle induced reactions that take place in thermonuclear explosions on the surface of accreting stars.

3.1. The hot CNO process and the αp-process

Thermonuclear explosions on the surface of accreting hot and dense stars such as white dwarfs or neutron stars are observed as novae or X-ray bursts, respectively. In both cases the explosion is triggered by the ignition of hydrogen burning at hot, dense, electron degenerate conditions driving a thermonuclear runaway that is fuelled by the hydrogen and helium content of the accreted material, until degeneracy is lifted. For novae, the energy release is primarily driven by the hot, or β-limited CNO cycles [14]; for X-ray bursts by the rapid proton capture or rp-process [15]. The time scale for the cataclysmic event is determined by the reaction rates and β-decays along the reaction path in the runaway event and is reflected in the steep rise of the characteristic light curves. The slow exponential decline of the light curve reflects the time scale of the decay of the longer lived radioactive isotopes produced during the event, and the associated energy release.
The interpretation of the nuclear physics processes underlying the sudden energy release in cataclysmic binaries is necessary for the understanding of these events. Experimental data are the key but that requires the careful study of many of the critical reactions in the hot CNO cycle and along the rp-process path. Most critical are the break-out reactions from the hot CNO cycles such as $^{15}\text{O}(\alpha,\gamma)^{19}\text{Ne}$ and $^{18}\text{Ne}(\alpha,p)^{21}\text{Na}$, which open the op- and rp-process that provide the source for the sudden nuclear energy release in the thermonuclear runaway [16].

The $\alpha p$-process is a series of $(\alpha,p)$ reactions, triggered by the $^{18}\text{Ne}(\alpha,p)^{21}\text{Na}$ reaction by which material flows out of the hot CNO cycle. Reactions like $^{22}\text{Mg}(\alpha,p)^{25}\text{Al}$, $^{26}\text{Si}(\alpha,p)^{29}\text{P}$, $^{30}\text{S}(\alpha,p)^{33}\text{Cl}$, and $^{34}\text{Ar}(\alpha,p)^{37}\text{K}$ determine the timescale of the thermonuclear runaway and therefore the shape of the X-ray burst light curves [17]. The $\alpha p$-process is replaced by the rp-process in the $Z=20$ range because of the increase in Coulomb barrier which reduces the probability for alpha capture. Presently the reaction rates are based on Hauser Feshbach predictions assuming a high level density in the associated compound nuclei. The density and characteristics of the alpha unbound states have been studied extensively by $(p,t)$ reactions using high resolution spectrographs [18]. The measurements are complemented by $(^3\text{He},n)$ studies using time of flight methods to obtain good neutron energy resolution [19]. Direct measurements are limited because they require the production of intense radioactive beams and the detection of the reaction products with high efficiency particle detection systems. First measurements of the $^{19}\text{Ne}(\alpha,p)^{22}\text{Na}$ reactions in inverse kinematics have been performed at the Louvain la Neuve radioactive beam facility [20]. These data only cover the higher energy range but the $^{20}\text{Ne}(^3\text{He},t)^{22}\text{Mg}$ measurements [18] indicate a decreasing level density towards the lower energy range. This makes the first extrapolation of the $^{18}\text{Ne}(\alpha,p)$ reaction cross section towards the stellar energy range highly uncertain; more data are clearly necessary to reduce the present uncertainties associated with the reaction rate. The situation is worse on the $\alpha p$-process rates towards higher masses, in some cases only very sketchy information is available about the level density and level structure, in particular in the Ca, Sc range which is associated with the endpoint of the process and the transition to the proton capture driven rp-process environment [21].

Transfer reaction studies only provide first estimates of the reaction rates, they are based on the determination of the level density and level energies but are handicapped by uncertainties in the determination of spin and parity of the resonance states and more important by the lack of knowledge about specific resonance parameters such as the alpha or proton partial widths that determine the resonance strength. Direct reaction studies are clearly an indispensable next step for providing reliable reaction rates. The first radioactive beam experiments [20] were based on the extensive use of Si strip detector arrays, a detection technology that is by now much improved, in particular due to the ability of designing much more complex strip-detector arrangements and handling larger count rates due to improvements in data acquisition capabilities.

To achieve higher resolution data a new instrument ANASEN has been developed for the direct study of these kinds of reactions [22] at future radioactive beam facilities. First tests have been performed at the FSU tandem accelerator facility, probing well known $(\alpha,p)$ reactions on stable nuclei such as $^{14}\text{N}$ with significant improvement in resolution compared to existing data. This indicates that ANASEN will be an important step for measuring particle reactions with unstable beams at future facilities such as ReA3 and FRIB.

### 3.2. The rp-process

The rp-process represents a sequence of proton capture reactions and $\beta$-decays along the proton drip line between the $Z=20$ and $Z=50$ closed shells. A detailed analysis of the nuclear physics related issues of the rp-process have been extensively discussed over the last decade [15, 16]. The role of the rp-process driving the thermonuclear runaway in an accreting neutron star (type I X-ray-burst) environment has been studied in the framework of a more realistic multi-zone model [23]. In this
paper it was shown that in a sequence of subsequent rp-process driven bursts the surface composition of the accreting neutron star is being altered and transformed from the initially predominately H, He, CNO composition to a heavy element abundance distribution in the mass $A=56$ to $A=100$ range.

Most of the nuclear processes associated with the rp-process are $(p,\gamma)$ radiative capture reactions. The reaction rates used for calculating the rp-process have been a matter of debate for years [24, 15, 25, 21]. While many of the rates have been estimated on the basis of existing nuclear structure data, most of them still rely on statistical model predictions. These carry large uncertainties since the level density of the compound nuclei near the proton-drip line is by no means well known and depends on the binding energies of the nuclei associated with the rp-process path. Of particular interest have been the even-even nuclei along the $N=Z$ line, such as $^{64}$Ge, $^{68}$Se, $^{72}$Kr which have been predicted to represent severe impedances for the rapid reaction flow because of the anticipated low or even negative $Q$-value of proton capture on these isotopes [15]. This translates in a substantial enhancement of the abundances of these waiting point nuclei, which is directly reflected in the abundance distribution of the r-process ashes as demonstrated in figure 5. For this reason improved mass measurements in the rp-process mass range have been a major goal of the community. Over the last decade substantial progress has been made by using ion trapping techniques (e.g. [26]) for high precision mass measurements of nuclei in the mass region of the waiting points and above for mapping the proton drip line that limits the rp-process path. These studies have been essential in establishing the exact pattern of the reaction path in that mass region and, most notably, in determining to what extend reactions such as $^{64}$Ge$(p,\gamma)^{65}$As, $^{68}$Se$(p,\gamma)^{69}$Br, and $^{72}$Kr$(p,\gamma)^{73}$Rb affect as waiting points the reaction pattern and the mass flow from the hot CNO region towards the higher mass regions within the short timescale of the burst [27].

![Figure 5](image)

**Figure 5:** rp-process abundance distribution after the first and the third rp-process driven burst. Details are discussed in Woosley et al. (2004) [23].

The end-point of the rp-process is associated with the $\alpha$-unbound nuclei in the Sb Te region [28]. Again, critical components to determine are the associated masses of the isotopes that affect the alpha
decay probability. While first experimental data [29] successfully provided information about the laboratory alpha decay-rate, the temperature conditions in the final phase of the burst are still sufficiently high to allow (p,α) reactions that initiate a cyclic burning pattern, the so-called SnSb cycle [28]. This depends again sensitively on the alpha thresholds in the associated compound nuclei being sufficiently low. An effective cyclic reaction pattern will release a second generation of α particles that in turn provide an additional final energy burst through the triple-alpha-process in which also 12C is formed. The 12C enrichment in the burnt rp-process ashes is thought to provide the fuel for the so-called superburst [30] observed in neutron star transients [31].

The time scale for the rp-process driving the initial burst phase is primarily determined by the β-decay times of nuclei along the proton drip-line. The proton capture reactions on the other hand determine the rp-process path and the flow pattern. Radiative capture processes in the mass range above 56Ni also influence the cooling conditions and the final abundance distribution of the rp-process ashes shown in figure 5. None of the radiative capture rates have been experimentally measured with the exception of the 21Na(p,γ)22Mg reaction that was studied in inverse kinematics using a 21Na beam provided by the ISAC radioactive beam facility at TRIUMF [8]. The 22Mg reaction recoils have been measured using the DRAGON recoil separator. This experiment demonstrated for the first time the versatility and selectivity of modern low energy recoil separator techniques for radiative capture measurements with radioactive beams. Unfortunately, the difficulties in the production of radioactive beams using the ISOL technique have limited the ISAC beam portfolio for more extensive rp-process reaction studies. For this reason most of the present reaction rates used for the calculations still rely on indirect structure measurements of the compound system or on statistical model predictions, which carry a substantial uncertainty in this mass range. To overcome these shortcomings, extensive plans have been made for the future FRIB radioactive beam facility to have a next generation recoil separator SECAR installed for studying the most critical radiative capture reactions along the rp-process path in inverse kinematics techniques and in particular for investigating possible β-decay proton capture branching points that may impact the reaction flow pattern and final abundance distribution in the rp-process ashes.

SECAR has been designed with the goal of measuring these capture reactions at very low energies using intense secondary radioactive ion beams using a high-density gas-jet target system. The conditions require large angular and energy acceptances of ± 25 mrad and ±3.1%, respectively. The separation of beam and reaction products is accomplished by first selecting one charge state and transmitting beam and reaction products with almost the same momentum. Two specially designed Wien-filters will be used for mass selection with a resolution of m/Δm=520 and m/Δm=790, respectively. This translates in an unprecedented “nominal beam suppression” of the order of ≥10^20, with further reduction by particle identification techniques in the detection system at the focal plane of the separator. Details will be presented in a forthcoming publication [32].

4. Conclusions and Outlook
The previous pages presented a number of experimental challenges and goals for the nuclear physicist interested in the field of nuclear astrophysics. This list of topics is by no means complete and has concentrated on questions associated with charged particle reactions in specifically selected stellar hydrogen and helium burning environments. There are a significant number of issues that have not been mentioned and that pose a number of additional challenging problems to the experimental nuclear astrophysics community. This includes the question about the low energy cross sections of heavy ion fusion reactions; these dominate late stellar evolution phases such as carbon and oxygen burning and are also crucial for understanding the ignition conditions for type Ia supernovae [33]. They are also being discussed as the most likely trigger for the recently observed superbursts in accreting neutron star environments [30]. The questions are primarily associated with the shape of the low energy cross section, if there is a hindrance factor which causes a rapid decrease in cross section due to nuclear incompressibility effects or if there are pronounced resonance effects caused by molecular cluster or dynamic fusion behaviour. The uncertainty about the low energy cross section
introduces significant uncertainties in the present modelling of heavy ion burning phases from late stellar evolution to explosive ignition [33].

The s-process in AGB star inter-shell burning environments is responsible for at least 50% of all the observed heavy elements above iron. Extensive measurements have been made over the last decades using a variety of experimental techniques to study the reaction rates of neutron induced processes with high accuracy [34]. While most of the s-process reaction rates have been discussed with great accuracy, the remaining uncertainties are associated with the question of neutron poisons that means neutron capture reactions on low Z isotopes that are highly abundant in s-process environments and can therefore significantly reduce by neutron absorption the effective neutron flux for the s-process. The other source of uncertainty is neutron capture on long-lived radioactive isotopes along the s-process path. The competition between neutron capture and beta-decay represents a number of important branching points along the s-process path. Comparison between observed and simulated isotope abundance distribution near the branching points can provide important information about the s-process environment [35].

There also remain a number of challenging questions about the p-process, which is associated with photo-dissociation of a heavy element abundance distribution in a hot stellar environment such as anticipated for type II or also type Ia environments [36]. The p-process is responsible for the production of the rarest neutron deficient stable isotopes (p-isotopes) above A=56. The contributing site or possibly sites for the origin of the p- isotopes remain a matter of debate, because of the remaining inconsistencies between the predicted and observed abundances on the $^{92}$Mo, $^{94}$Ru and other isotopes in this mass range. Most of the photo-dissociation rates rely on statistical model predictions. The existing experimental studies have been confined to the measurements of photo-dissociation and radiative capture as inverse process on stable nuclei and most of the results agree with the model predictions. Future studies will focus on the more challenging measurements on short-lived isotopes along the predicted p-process path to test if the use of statistical reaction rates remains viable [37]. First experiments at the GSI storage ring suggest a promising path towards this goal [38].

The biggest remaining challenge for future studies remains the r-process. In the past most of the experiments have focused on life-time and β-decay measurements of isotopes along the r-process path. These are complemented now with high precision mass measurement using storage ring or trapping techniques. These techniques will bring full fruit when coupled to the next generation of high intensity radioactive beam facilities and will improve our knowledge on r-process nuclei along the r-process path. A recent study identified the nuclei where mass measurements will have a major impact on r-process abundance predictions [39] While this is a very satisfying development, a second generation of experiments is necessary, testing the predicted neutron capture reactions on very neutron rich isotopes, which may shift the anticipated r-process abundance distribution after freeze-out. Two techniques are presently being investigated, inverse photo-dissociation measurements using virtual photons [40] or (d,p) surrogate transfer reaction studies [42]. Both techniques fail to grasp the all of the possible interfering resonant and non-resonant reaction components and γ-decay branches that characterize a radiative neutron capture process. The measurements therefore need to be coupled with sophisticated next generation reaction theory and structure models to translate the results of the ($γ,n$) photo-disintegration or (d,p) transfer studies into reliable (n,$γ$) radiative capture predictions [42]. This represents both an experimental as well as theoretical challenge and a number of systematic tests on well-established neutron capture cases will be necessary to verify the applicability of this approach.

Weak interaction plays a crucial role in dense stellar environments. Electron capture processes trigger the core collapse of type II supernovae [43] and play a crucial role for the fate of the ashes of the rp-process in the neutron star crust possibly providing a nuclear heat source that affects the cooling pattern of x-ray burst transients [44]. Neutrino induced processes are predicted to leave its fingerprints on the detailed structure of the r-process abundance distribution and neutrino interaction may play a role in energy budget of dense neutron star crust matter. This represents new experimental challenges to the community. New experimental methods have been developed; charge exchange reactions have emerged as a powerful probe to explore experimentally the strength of weak interaction driven decay.
and electron capture reactions [45], high resolution electron scattering experiments may provide the tool for probing inelastic neutrino scattering processes [46]. The new experimental probes are presently tested at stable isotopes; future radioactive beam facilities will be essential to expand the measurements into the range of explosive nucleosynthesis patterns which presently can only be simulated on the basis of decay measurements and theoretical estimates.

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