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Neutron-star mergers and new opportunities in rare isotope experimental research

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ABSTRACT

The recent observation of the first neutron-star merger event GW170817 had major impact on our understanding of stellar nucleosynthesis. It was identified for the first time as one of the sites for the astrophysical r process, a process that is responsible for the synthesis of roughly half of the isotopes of the heavy elements. The observed kilonova afterglow from the neutron-star merger event was interpreted as the result of the radioactive decays of r-process isotopes as they decay back to the valley of stability. The observed kilonova light curve is however broad due to its complex composition and the Doppler-shift due to fast moving matter, and is therefore impossible to interpret without accurate knowledge of the nuclear properties of the nuclei involved. This work focuses on the current experimental efforts to measure the relevant nuclear properties, together with plans for the next generation radioactive beam facilities, and in particular the Facility for Rare Isotope Beams (FRIB).

1. r-process nucleosynthesis

The question: "Where do we come from?" has been puzzling humankind throughout its history. From the ancient civilizations to modern times, scientists and philosophers alike have been trying

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to give an answer to this basic question. When it comes to explaining the origin of the atoms in our bodies, on our planet, in our solar system, and in general the whole Universe, the answer can simply be: "We come from the stars". Other than the lightest elements that were made during the Big Bang, all other elements are cast inside stellar ovens through nuclear reactions and decays. This fundamental discovery was made back in the 1950s [1] when Paul Merrill first observed Tc lines in a star. Since Tc has no stable isotopes, this observation indicated that the star itself must be producing the technetium, opening a whole new window into the Universe, one that combines our astronomical observations, our astrophysical models and our nuclear physics knowledge, to continue to answer the basic question: "Where do we come from?".

The first comprehensive description of the astrophysical processes that synthesize the elements in stars was done in 1957 by two independent works. Burbidge, Burbidge, Fowler, and Hoyle [2] and in parallel Cameron [3] described stellar nucleosynthesis from the lightest elements up to the heaviest ones. Their original description is still mostly valid, although many things have changed in the 60 years since.

Today we know that elements lighter than iron, are mainly formed during the evolution of a star, in nuclear processes that are considered "quiescent" nucleosynthesis (non-explosive). During these processes, nuclei fuse together to form heavier nuclei. Supernovae Type Ia also contribute to the synthesis of elements around the iron peak. Above iron, nucleosynthesis requires different processes, ones that do not involve the capture of charged particles and are therefore not hindered by the Coulomb barrier. Therefore, neutron-induced reactions dominate the synthesis of heavy elements, with some contributions from photo-dissociation. Three processes are considered as the dominant contributors to heavy element nucleosynthesis, namely the "slow neutron-capture process" or "s process" [4], the "rapid neutron-capture process" or "r process" [5,6] and the "p process" which is responsible for making only about 35 proton-rich isotopes that cannot be formed by the s or r processes [7,8]. Here we will focus on the r process, which is responsible for the production of about 50% of the isotopes of elements heavier than iron, and until recently has been the most elusive.

From early on it was clear that the astrophysical r process must involve very exotic neutron-rich nuclei. This conclusion came from making the connection between apparent peaks in the abundance distribution of r-process nuclei at mass 80, 130, and 195 [9], and nuclear structure properties. Specifically, each of these peaks is formed when the reaction flow during an r-process event passes through one of the neutron magic numbers 50, 82, and 126. Nuclei with neutron magic numbers show enhanced stability compared to their neighboring nuclei, and as a result the reaction flow stalls there, allowing an accumulation of r-process material that can be transferred to the next isotopic chain via β decay. When the drop in temperature and neutron density occurs, the r-process "freezes out" and the neutron-rich material decays back to stability. The resulting abundance pattern carries the signatures of these neutron-magic number encounters, forming the corresponding peaks. This procedure is also true for the s-process, only in this case the reaction flow proceeds along stable nuclei, and the resulting abundance peaks appear at slightly heavier masses ($A = 90$, 138 and 208) [4].

The connection between r-process abundances and nuclear physics properties puts strong constraints on the conditions required for an r process to take place. Extreme neutron densities ($>10^{20}/\mathrm{cm}^3$) and short time scales (of the order of a few seconds) are essential for pushing the reaction flow into very neutron-rich nuclei and far from the valley of stability. However, finding the astrophysical environments that can fulfill these conditions was more challenging, and took more than six decades to resolve.

Among the many scenarios proposed as possible r-process hosts, core collapse supernovae and neutron-star mergers were the most popular ones. It is beyond the scope of the present review to discuss the history and developments in r-process astrophysical calculations. The reader is referred to a recent review of the topic [10]. While contributions for different sites are still under discussion, in 2017, a definite site for the r process was unambiguously identified during the first observation of the neutron-star merger event GW170817 [11], in agreement with earlier interpretation of r-process element observations in the Reticulum II dwarf galaxy [12].

Three gravitational-wave observatories and ninety telescopes from around the world, and in space, observed GW170817 and the corresponding astronomical transient AT 2017gfo, and identified it as the merging of two neutron stars [13–16]. Together with the properties of the neutron-star system itself, a unique signature of r-process nucleosynthesis came in the "kilonova" afterglow of the event, which corresponds to the direct observation of radioactive decays of neutron-rich nuclei [11]. This is the first time that the scientific community has observed an r-process signature other than elemental abundances, and it offers a rich ground for further understanding heavy element nucleosynthesis in these events. The kilonova signal is divided in two groups, a so called "blue kilonova" (optical), and a "red kilonova" (infrared). The blue component corresponds to the decay of lighter elements and fades away within a few days, while the red component lasts longer (a few weeks) and is the signature of heavier elements, namely lanthanides, for which the complex atomic structures result in higher opacities, causing the emitted radiation to be shifted in wavelength. The kilonova emission was predicted a few years earlier [17–19] and was one of the most significant r-process discoveries in decades.

The kilonova observation, although extremely significant, is still not the end of the road. The observed spectra are broad, having contributions from a large number of radioactive decays, and they are additionally distorted by the Doppler shift of fast moving material [16]. It is practically impossible to extract the composition of the decaying isotopes from the astronomical observations. The kilonova light curve will be significantly affected by the decay properties of the nuclei involved, but also by the exact r-process path far from stability. In addition, the r-process path itself will be affected by the nuclear properties of the participating nuclei, such as their masses, β-decay properties, neutron-capture rates, and fission properties. For this reason, it is of paramount importance to have accurate nuclear physics data, to be able to predict the r-process path accurately. With this, the distribution of decaying isotopes that contribute to the kilonova lightcurve can be extracted. The last missing piece for a complete understanding of the lightcurve are the elemental opacities which are so far solely based on theoretical predictions for heavy elements.

The present article highlights the nuclear input needed to understand r-process nucleosynthesis (Section 2). It discusses the current experimental efforts to provide accurate and relevant nuclear data for r-process calculations (Section 2), and presents new opportunities that will be possible in the future with the next generation rare isotope facilities, and in particular the Facility for Rare Isotope Beams (Section 3).

2. Sensitivity to nuclear input

The nuclear input necessary for r-process calculations can be found if we consider a simple r-process path and the possible nuclear reactions and decays that drive it. A schematic view of these properties on the nuclear chart is shown in Fig. 1. Neutron-capture reactions and β^- decays are the two main competitors. The flow is defined based on which of the two competitors is faster. Therefore, the quantities of importance are the neutron-capture reaction rate, and the β-decay half-life ($T_{1/2}$). If the β^- decay happens to populate states in the daughter-nucleus that are above the neutron separation energy, then β-delayed neutron emission can occur (βn). The probability for βn decay becomes more important farther from stability, and could result in the emission of a single or multiple neutrons. The various β-delayed neutron emission probabilities define the final mass chain that will be populated after the decay, and they also replenish the environment with fresh neutrons that can induce more neutron-capture reactions at later times. If the temperature is high enough, the inverse neutron-capture reaction can take place, namely the (γ,n) reaction. Finally, if the conditions are such that the heaviest masses ($A > 260$) are reached, nuclear fission can have a significant role by driving these heavy masses back to lighter nuclei (fission fragments) to serve as fresh r-process seeds.

The astrophysical conditions for the r process can be divided into two general categories: hot and cold. In a hot r process, the temperatures are high enough for (γ,n) reactions to occur. These reactions balance their inverse, neutron-capture reactions, and the reaction flow takes place in a $(n, \gamma) \Leftrightarrow (\gamma, n)$ equilibrium. In this case, the impact of neutron capture reactions is not important, at least at early times, while the equilibrium lasts, and the r-process flow is defined by neutron-separation energies $S_n(Z, A) = E_B(Z, A) - E_B(Z, A - 1)$, where $E_B(Z, A)$ is the binding energy of a

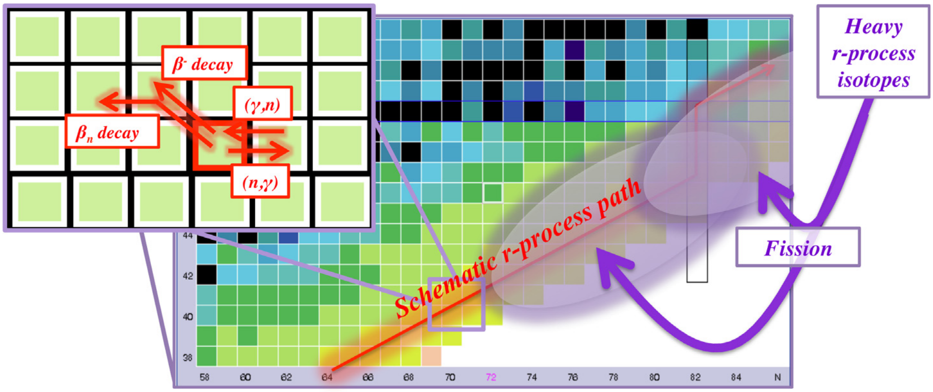

Fig. 1. Schematic view of the various competing nuclear reactions and decays that drive the r process. At any point, the r-process path will be defined by which one of these reactions/decays wins over the others. Nuclear fission is displayed on the right-hand side, showing schematically how it replenishes the lighter masses with fission products in characteristic fission-fragment distributions.

nucleus. Under such an equilibrium, a steady flow of β^- decays occurs [20], including β-delayed neutron emission. During the freeze-out phase when the temperature and neutron-density drop, the $(n, \gamma) \Leftrightarrow (\gamma, n)$ reactions drop out of equilibrium. At this phase neutron-capture reactions become important, and their competition with β decay defines the final abundance pattern.

On the other hand, under cold conditions, where photodisintegration reactions are not significant, $(n, \gamma) \Leftrightarrow (\gamma, n)$ equilibrium is not reached. In this case, neutron-capture reactions compete with β decays and push the r-process flow further away from stability, approaching the neutron-drip line. Therefore, the properties of even more exotic nuclei become important, and the final abundance distribution depends strongly on the competition between neutron-capture reactions and β decays.

It is clear that no matter what the specific r-process conditions are, nuclear properties drive the reaction flow and define sensitively the shape and amplitude of the peaks in the final r-process abundance distribution. In the following, the individual nuclear properties will be discussed in more detail, to show their importance to the r process.

To identify the impact of each nuclear property and even each isotope, one needs to perform sensitivity studies, in which nuclear properties are varied systematically within their uncertainties and compared to a baseline calculation to study how the final abundances are affected. A comprehensive r-process sensitivity study was recently performed by Mumpower et al. [21], showing the sensitivity to nuclear masses, β-decay properties, neutron-capture reactions and nuclear fission. Each of these properties will be discussed in Sections 2.1–2.4. In addition, the experimental techniques to measure each quantity will be presented, together with some recent results.

2.1. Nuclear masses

Nuclear masses play a fundamental role in r-process modeling, as they affect most of the involved nuclear properties. Binding energies, β-decay Q-values, half-lives, neutron-capture rates, and nuclear fission, are all quantities that are affected by changes in nuclear masses. In the Monte Carlo sensitivity study by Mumpower et al. [21] it was shown that the r-process abundance uncertainties due to variations in the prediction of nuclear masses are larger than with any other property. In this work, the authors used well known mass models, and varied the masses within each model's quoted root mean square (rms) error when compared to measured nuclei ($\approx$ 500 keV). The resulting uncertainty in the final abundance distribution was more than two orders of magnitude in some cases. The uncertainty band is not uniform, something that was also observed in the work by Martin et al. [22]. These authors also noted that the uncertainty band is affected more strongly around nuclear shell closures, and in the regions where the nuclear structure changes between deformed and spherical nuclei.

In addition to the overall impact of nuclear masses on the final abundance distribution, Mumpower et al. [21] also calculated the sensitivity of changes in the mass of a single nucleus on the abundance curve and extracted sensitivity factors for different astrophysical scenarios. Such studies are of paramount importance for guiding experimental programs, so that future facilities and new equipment can be optimized to measure the most important nuclei. Unsurprisingly, nuclei around magic numbers have a larger impact, due to the fact that the reaction flow stalls in these regions, allowing r-process material to build up and decay into the next isotopic chain, creating the well known abundance peaks.

A new approach to nuclear mass investigations has been applied recently in the form of "reverse engineering" [23]. In this approach the authors modify systematically the mass predictions in certain areas of the nuclear chart (in this case around the so called "rare-earth peak") until the new masses can reproduce the observed abundances. The new masses are then compared to experimental data, and in the recent work by Orford et al. [23] were found to be in excellent agreement. With this approach the authors show that some distinct features of the r-process abundance distribution are a result of potential nuclear structure changes in the region, although the exact nature of these nuclear structure features cannot be inferred from this investigation. Additional calculations for a broader range of astrophysical conditions are under way.

An important aspect of sensitivity studies, on top of identifying which nuclei are important, is to estimate how accurately one needs to calculate or measure a particular quantity. In the case of nuclear masses, while theoretical models can reproduce known masses within roughly 500 keV, the required accuracy is estimated to be closer to $\approx$ 100 keV [21]. This is also a good guide for designing experiments to measure the masses of r-process nuclei.

A large number of experimental techniques have been developed over the years to measure nuclear masses, with precisions that vary from 1 up to a few hundred keV. Typically, more accurate techniques require higher beam intensities and longer times, and can only measure one isotope at a time. Less accurate techniques have the possibility of measuring tens of isotopes simultaneously and can be applied to the shortest-lived isotopes on the nuclear chart. An extended description of these techniques and how they relate to r-process needs was done recently in Ref. [10], and they will be presented here only briefly.

Penning Trap Measurements: The main idea of penning-trap measurements is that an ion is trapped inside strong magnetic and electric fields, where it performs a cyclotron motion. The motion depends strongly on the ion's mass, and through constraining and calibrating all parts of the experimental setup, one can extract the mass of the ion with accuracies that reach 1–10 keV [24–26]. With such high accuracies, penning trap measurements can also provide measurements for isomeric states within a nucleus. On the other hand, to achieve this level of accuracy, penning trap measurements take a relatively long time per ion ($\sim$ 0.5 s), and therefore cannot easily be applied on isotopes with half-lives less than about 100 ms.

Due to the success of this technique, penning trap setups have been implemented in most of the major radioactive beam facilities around the world: ISOLTRAP at ISOLDE [27], JYFLTRAP at Jyväskylä [28], TITAN at TRIUMF [29], LEBIT at Michigan State University [30], CPT at Argonne National Laboratory [31]. Recently, a new method of penning trap mass measurements has been developed, called "phase imaging ion cyclotron resonance" (PI-ICR) [32–35]. This technique is much faster than the traditional penning trap measurements and has been implemented in most major facilities.

Storage Ring Measurements: In storage ring facilities, masses are determined from measuring the revolution frequency of the ions in the ring [36]. While the precision of these mass measurements is not as good as in penning traps (a few 100 keV), it is still within the requirements for r-process needs. In addition, the technique has the major advantage that, in principle, it can be used to measure multiple masses simultaneously.

Two approaches have been developed for measuring masses in storage rings. The Schottky Mass Spectrometry (SMS) method has been used with the experimental storage ring (ESR) at GSI

Darmstadt, Germany [37]. SMS requires cooling of the beam before performing the measurement, which takes a significant amount of time, and as a result cannot be applied to nuclei with half-lives shorter than about 1 s. As an alternative, the Isochronous Mass Spectrometry (IMS) method was developed [38], and can measure the shortest-lived nuclei involved in the r process, down to less than a ms.

Together with GSI, Darmstadt, Germany, storage rings are used for mass measurements at the Institute of Modern Physics, in Lanzhou, China [39,40] and at RIKEN, Japan [41].

Time-of-Flight Measurements: Various setups and techniques are available for measuring nuclear masses using the Time-of-Flight (ToF) of ions. Traditional ToF experiments measure the time it takes for the ion beam to travel from one point of a facility to another [42,43], while more modern versions use multi-reflection spectrometers (MR-ToF) to achieve a longer flight path [44], and therefore better accuracy. The main advantage of the ToF technique is the fact that it can be used to measure a large number of nuclei simultaneously. In these experiments, nuclei of known masses are used as calibration points, while measuring new masses at the same time. Another advantage is that ToF measurements are relatively fast (within roughly 100 ns), and therefore it can be used to measure the masses of very short-lived isotopes. On the other hand the precision of the technique is not as high as penning-trap measurements. The traditional ToF measurements provide masses within roughly 300 keV, while the modern successor, MR-ToF, has a better accuracy, down to 20–150 keV. MR-ToF devices are also used in radioactive-beam facilities around the world (such as ISOLDE, RIKEN, ANL, TRIUMF) as isobar separators for purifying the beam for other experiments, such as penning-trap measurements.

2.2. β-decay properties

β-decay half-lives and β-delayed neutron emission probabilities are two additional quantities that are important inputs to r-process calculations. Half-lives, especially in cold environments, define the reaction path through the competition with neutron-capture reactions. On the other hand, β-delayed neutron emission redirects the flow of matter back to stability, by shifting the decay path by one or more neutrons. In addition, the emitted neutrons can induce additional neutron-capture reactions at late times, during freeze-out.

The half-life of a nucleus is typically the first quantity measured, following the discovery of an isotope. It can be done with a very small number of detected nuclei, typically by measuring the time between the detection of an implanted ion and the detection of a decay electron, correlated in time and space. These measurements can also be combined with measurements of γ radiation to establish a characteristic level scheme and provide nuclear structure information. Finally, combined with a neutron detector, these experiments can provide a measure of the β-delayed neutron emission probability. In particular, to measure the total neutron branching without detailed neutron-spectroscopy, β-delayed neutron experiments can be performed with very low beam intensities, down to 10^{-5} pps.

While decay measurements are done at all major facilities around the world, during the last few years, the RIKEN laboratory in Japan has pushed the limits of known half-lives further than any other facility. With over 200 new half-lives in the mass region between 70 and 160 [45–48], these measurements clearly show the power of new radioactive beam facilities, and have provided access to a significant number of nuclei along the r-process path for the first time. On top of measuring new half-lives, the new RIKEN results also showed the importance of re-measuring already known half-lives, revealing discrepancies with older measurements (e.g. [47]). The higher beam intensities at RIKEN also provided an opportunity for new β-delayed neutron emission measurements using the BRIKEN setup [49]. Many other detector setups are used around the world for measuring decay properties, but cannot all be described here. A more comprehensive description was done recently in Ref. [10].

One unique approach that has recently been developed at Argonne National Lab (ANL) for β-delayed neutron emission measurements makes use of a Paul trap [50,51] to detect the recoiling ions instead of the emitted neutron. Both the emitted electrons and the recoiling nucleus are detected using appropriate detectors that surround the trap. The time difference between the

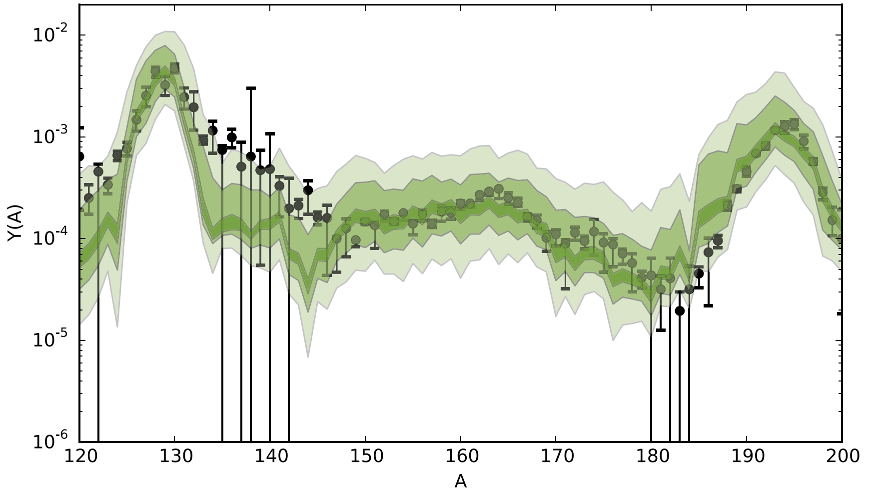

Fig. 2. Monte Carlo sensitivity of r-process abundances to neutron-capture reactions. The (n, γ) variation was a factor of 100 (light band), 10 (medium band), and 2 (dark band). The calculations were done for a neutron-star merger scenario. *Source:* Figure from Ref. [52].

electron and ion detection, yields two distinct distributions. The fast-time component corresponds to the neutron emission because in this case the recoil gets a larger "kick" from the emitted neutron, while the slow component corresponds to the recoiling nucleus after β emission. The advantage of the technique is that one can extract the neutron energy spectrum, not just the neutron branching, however the method is limited to single neutron emission cases. The technique was successfully implemented [51] at ANL and is currently under further development to improve the efficiency of the setup.

2.3. Neutron-capture rates

As mentioned earlier, neutron-capture reactions play an important role in the r process, either at late times during freeze-out, or for the whole duration for the cold r process. In a hot environment, where $(n, \gamma) \Leftrightarrow (\gamma, n)$ equilibrium is established, the important neutron-capture reactions take place on nuclei closer to stability, while in a cold environment, the important neutron-captures can extend further from stability. The sensitivity study of Mumpower et al. [21] presented the important (n, γ) reactions for various astrophysical conditions (Fig. 16 of Ref. [21]). In this study it is clear that under all astrophysical conditions, nuclei around closed neutron shells have a larger impact, although nuclei between the N = 82 and N = 126 magic neutron numbers can also be important. For example, in the region of the rare-earth peak, neutron captures around A = 160 were also shown to be important. Many of these isotopes are currently accessible at the CARIBU facility at Argonne National Laboratory, and even more will become available with FRIB in the future.

For a neutron-star merger scenario, the impact of a Monte Carlo variation of neutron-captures on the final abundance distributions was presented in Liddick et al. [52], and is also shown in Fig. 2. Assuming that all neutron-capture reaction rates have an uncertainty of a factor 100, the light-colored band in Fig. 2 shows the variation this uncertainty would cause to the final r-process abundances. Assuming an uncertainty of a factor 10, the results are shown in the medium-dark color, while the darkest color represents a variation of neutron-captures within a factor of 2. It is clear that neutron-capture reactions need to be constrained to within roughly a factor of 2, if we want to be able to constrain r-process abundance distributions accurately.

Unlike masses and β-decay rates, neutron-capture reaction measurements are not only limited by beam availability and beam rates. A fundamental issue with measuring an (n, γ) reaction on a short-lived nucleus is that it is not possible to make a target out of any of the two reactants. Both, the neutron and the rare isotope can be made available as beams, however, no facility is currently able to produce both beams at sufficient quantities for a beam-on-beam type experiment. Recently, some ideas for coupling a rare-isotope storage ring with either a reactor [53], or a spallation neutron source [54] have been proposed, however, no firm plans exist for such facilities at this time.

With the lack of direct techniques for neutron-capture reaction measurements far from stability, indirect methods need to be developed. The main idea of these techniques is to use different probes to study either the reaction mechanism, or the nuclear structure of the nucleus of interest, and use this information to constrain the (n, γ) reaction. Several approaches have been developed for this purpose, and some of the most recent ones that can be applied for r-process nuclei will be presented here. A more comprehensive description of novel techniques for constraining neutron-captures for the r process was presented in Ref. [55].

It should be noted that for the majority of the relevant nuclei, the nuclear statistical model can be used to calculate the (n, γ) reaction cross sections, due to their relatively high level density [56]. Within this approach, it is assumed that the outgoing channel of the reaction (γ emission in this case) is independent of how the nucleus was formed, and its decay is governed by statistical properties. As long as this assumption is valid, many indirect approaches can be used to study the statistical decay of the compound nucleus, and in this way constrain the neutron-capture reaction. Together with the Optical Model Potential (OMP) that is important for the ingoing channel, the two main quantities that are needed are the Nuclear Level Density (NLD) and the γ-ray Strength Function (γSF). These quantities are the main focus of indirect techniques. On the other hand, around neutron-magic numbers and close to the dripline, the nuclear level density is smaller, and direct capture, or individual resonances become more important. In this case, the (d,p) reaction can be used as a surrogate to probe the direct reaction contribution of the neutron-capture (see e.g. [57,58]). In the following, four techniques will be discussed that are all focused on the assumption of statistical behavior of the nucleus.

Coulomb dissociation: In a Coulomb dissociation reaction, an ion beam impinges on a heavy target (typically Pb), the beam nuclei get excited through the Coulomb interaction with Pb (virtual photon excitation), and de-excite emitting either γ rays or neutrons. Experiments done at GSI, Darmstadt, used this technique to deduce the photoneutron cross section and extract giant dipole resonance and pygmy resonance parameters for neutron-rich Sn isotopes [59] and for ^{68}Ni [60,61]. These experiments provide unique information about the γ-ray strength function above the neutron threshold using radioactive beams. Additional measurements for a broader range of nuclei would be desirable.

Surrogate technique: In the surrogate technique, instead of the direct capture of a free neutron, the neutron is “sneaked” into the target nucleus through the interaction with a deuteron, while the proton escapes and can be detected. This technique was successfully used for years to study neutron-induced fission [62], however until recently it could not provide accurate neutron-capture reaction cross sections. A recent breakthrough based on the appropriate treatment of spins and parities in the compound nucleus [63] was successful in using a (p,d) reaction to populate the nucleus of interest and extract a neutron-capture reaction cross section that agrees with direct measurements. This technique can also be used in inverse kinematics using radioactive beams, and is therefore very promising for neutron-capture measurements for the r process. The beam intensity needed to apply the surrogate technique is of the order of 10^4 pps.

Oslo method in inverse kinematics: The Oslo method is a well known technique that provides the nuclear level density and γ-ray strength function of the populated nucleus [64,65]. In the past it has been used at stable-beam facilities in regular kinematics where a light beam particle would interact with a heavy target. The light reaction product is detected using an array of Si detectors, while the γ rays from the deexcitation of the populated nucleus are detected in an efficient γ-ray detector array. The basis for the Oslo analysis is a 2D matrix of excitation energy vs γ-ray energy. Following the unfolding [66], iterative subtraction [64], and normalization [65,67,68], the nuclear level density and γ-ray strength function are extracted. These two quantities are then used in a statistical model calculation to provide an experimentally constrained neutron-capture cross section.

Recently, significant effort was devoted to extending the traditional Oslo method to radioactive nuclei for r-process studies. The first step was a proof-of-principle experiment done at iThemba

Labs in South Africa using a ^{86}Kr beam impinging on a deuterated polyethylene target [69]. The ^{86}Kr(d,pγ)^{87}Kr reaction was used to populate the compound nucleus ^{87}Kr and extract its nuclear level density and γ-ray strength function. The experiment was successful and the results will be submitted for publication soon. Following the successful proof of principle, the first radioactive beam experiment was performed at HIE-ISOLDE at CERN, using a ^{66}Ni beam impinging on a CD_2 target mounted in the MINIBALL array [70]. Two reactions were studied in this experiment, namely the ^{66}Ni(d,pγ)^{67}Ni and ^{66}Ni(d,tγ)^{65}Ni, aiming at extracting the NLD and γSF for the two produced nuclei ^{67}Ni and ^{65}Ni. The analysis of this experiment is ongoing. This pioneering experiment using the Oslo method in inverse kinematics paves the way for more radioactive beam experiments at HIE-ISOLDE, and other facilities around the world.

Radioactive beam experiments are always limited by the available beam rates, as well as the need to use relatively thin targets to achieve good energy resolution. A new approach is under development by the University of Guelph, TRIUMF laboratory, Colorado School of Mines and the Technical University of Munich, which will enhance the reaction yield, while maintaining the required energy resolution. The TIGRESS Silicon Tracker Array (TI-STAR) [71] will be a compact detector inside the TIGRESS γ-ray spectrometer [72,73]. The detector will host an extended deuterium gas target, surrounded by a silicon tracker. Due to its tracking capabilities, TI-STAR will allow the reconstruction of the interaction point, maintaining a good energy resolution, while enhancing the reaction yield by factors of 10–100. This approach is planned to be implemented first at the TRIUMF laboratory in Canada.

While transfer reactions can be used in inverse kinematics at energies of the order of a few MeV/u, different types of reactions need to be used at fragmentation facilities that typically offer beam energies of the order of 100 MeV/u. Recently, the charge exchange reaction has been investigated as a possible reaction to populate the compound nucleus of interest and apply the Oslo method to extract NLD and γSF. Preliminary results using the ^{46}Ti(t, ^{3}Heγ)^{46}Sc reaction measured with the GRETINA γ-tracking array [74] at the NSCL [75,76] look promising and more experiments are being planned for the near future.

β-Oslo: While the aforementioned techniques are all reaction-based, a new approach was developed recently by groups at Michigan State University and the University of Oslo, which uses the β decay of a radioactive nucleus to populate the compound nucleus of interest, and apply the Oslo method to extract NLDs and γSF. This so-called β-Oslo method [77] uses a segmented γ-ray calorimeter (SuN at the NSCL [78]) to determine the excitation energy of the nucleus, while providing information about the individual γ rays emitted. The main advantage of the technique is the fact that it uses β decay to populate the nucleus of interest, and can therefore be applied with very low beam intensities, down to 1 particle per second, which is not possible with the reaction-based techniques. On the other hand, the technique is limited by the available energy window for the decay (β-decay Q-value) which can be very small close to stability, and also by the neutron separation energy, which decreases while moving into more neutron-rich nuclei.

The β-Oslo technique has been performed so far for nuclei in the weak r-process region [79] around $A = 70$ [52,80]. In parallel, significant efforts have been devoted to validating the technique against the traditional Oslo method, other indirect techniques, and also against direct (n, γ) measurements [81–83]. While the results so far have been very encouraging, more validation measurements at higher masses are needed.

2.4. Nuclear fission properties

When the r-process reaction flow reaches heavy nuclei in the actinide region around A≈260, then neutron-induced fission becomes possible, resulting in a process known as fission recycling. In this process, fission fragments replenish the available nuclei at lighter masses, which in-turn serve as new seeds for the r process to continue to synthesize heavier nuclei. Fission recycling has been proposed as the reason for the apparent robustness of r-process abundance distributions of heavy elements in old stars [6,84,85]. The signature of this robustness is the consistent abundance distribution in metal poor stars for elements above barium. Lighter elements exhibit a larger variation and that is an indication of contributions from more than one processes. A recent review of metal-poor star observations can be found here [86].

When fission recycling is possible, nuclear fission properties become an important input to r-process calculations, and more specifically the fission barriers and fragment distributions as discussed in the reviews of Horowitz et al. [10] and Andreyev et al. [87], and references therein. Depending on the fission-barrier amplitudes, the r process might be terminated due to the fission process, or, if the barriers are high, the reaction flow can proceed to heavier masses before fission reactions are triggered. Therefore, fission barriers are the defining factor for where the r-process flow will get terminated and how heavy the produced nuclei will be.

Unfortunately, the involved nuclei are quite far from the regions of the nuclear chart that are accessible with current facilities. Experiments near the valley of stability can be used to inform the theoretical calculations, however, fission properties for r-process nuclei have to rely almost exclusively on theory. A discussion on the possible experimental efforts related to fission can be found in [10].

3. The future: the facility for rare isotope beams

When looking into the nuclear data needs for the astrophysical r process, it is clear that no single group and no single facility can provide access to the full set of required data. The nuclear astrophysics community has been successfully taking advantage of the complementarity of different rare isotope laboratories around the world and their unique capabilities in terms of beam production and experimental equipment. It is beyond the scope of the present work to discuss in detail all available facilities and instrumentation. Some descriptions were provided in previous sections in the context of required measurements, however the list is far from complete. For more details, the reader is referred to two recent works that include "facilities" sections [10,55]. Several next generation rare isotope facilities are planned, such as the Advanced Rare Isotope Laboratory (ARIEL) facility in Canada, the Facility for Antiproton and Ion Research (FAIR) in Germany, the RIKEN upgrade in Japan, Heavy Ion Research Facility at Lanzhou (HIRFL) in China, and the Rare isotope Accelerator complex for ON-line experiment (RAON) in South Korea. Here we will highlight the Facility for Rare Isotope Beams (FRIB), which is under construction in the United States.

FRIB is currently being constructed on the campus of Michigan State University with funding from the Department of Energy Office of Science, the State of Michigan, and Michigan State University. It is expected to be completed in 2022 and will replace the existing National Superconducting Cyclotron Laboratory (NSCL). The heart of FRIB will be a 200 MeV/u superconducting linear accelerator which is expected to provide beam power of up to 400 kW for beams up to uranium. FRIB is expected to exceed NSCL rare-isotope beam rates by at least three orders of magnitude, offering access to rare isotopes that have never before been observed. A future energy upgrade of FRIB to 400 MeV/u is expected to increase the beam rates even further (Fig. 3). As mentioned in the FRIB400 whitepaper [88], the gain from a 400 MeV/u upgrade is manifold: "*Significant gains in isotope production will be realized by increasing the primary-beam energy from 200 to 400 MeV/u, nearly doubling the reach of FRIB along the neutron dripline; (ii) in heavy-ion reactions, dense nuclear matter can be studied up to twice saturation density, critical for multi-messenger astrophysics; (iii) in reaction experiments, thicker targets can be used, increasing the luminosity for measurements and so extending their reach significantly; and (iv) nuclear reactions can be performed in a regime of optimum nuclear transparency, improving their interpretation by reaction theory.*"

In particular for the r process, FRIB will give access to the majority of neutron-rich isotopes along the r-process path, while at the same time providing higher beam intensities for isotopes that are already known but not accessible for certain types of experiments that require higher beam intensities. The FRIB reach can be seen in Fig. 3, where the chart of nuclei is color-coded with the projected FRIB beam rates for the 400 MeV/u upgrade. Isotopes marked in red color correspond to primary beams, and the black line shows the reach of current facilities. A schematic r-process path is also shown to guide the eye, showing the extend of FRIB's capabilities far beyond what is currently known and reaching most of the r-process isotopes. At the bottom-right corner, the different techniques presented here are highlighted with the color that corresponds to the minimum beam intensity needed, as described in Section 2.

Together with the new beam capabilities, it is important to develop appropriate equipment to take full advantage of FRIB for r-process measurements. Some of the required experimental

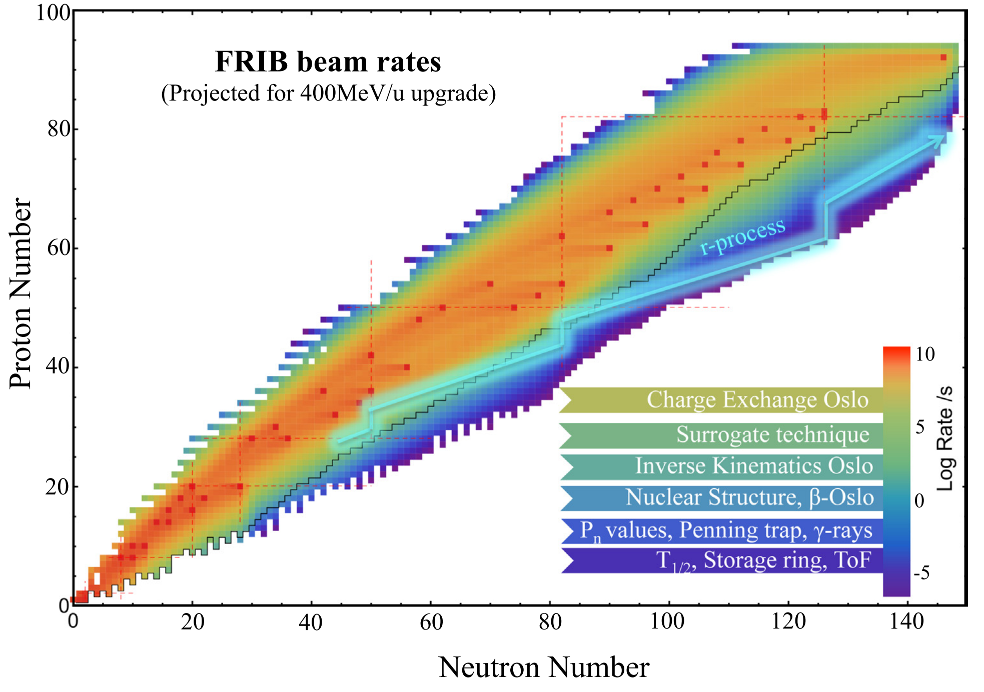

Fig. 3. Projected FRIB beam rates for the 400 MeV/u upgrade [93]. At the bottom-right corner the different techniques are highlighted with their required beam rates in a rough schematic presentation.

setups are already available and in use at the NSCL, such as the LEBIT Penning trap [30], and S800 spectrograph for mass measurements, the SuN γ-ray calorimeter [78] for β-Oslo neutron-capture measurements, the NERO detector [89] for β-delayed neutron emission measurements, the Beta Counting System (BCS) for half-life measurements [90], and many more. In addition, community developed equipment can be installed at FRIB and be used for experiments. Finally, new equipment developments in the field will enhance the current capabilities, like the High Rigidity Spectrometer (HRS) [91], the GRETA γ-ray tracking array [74], and the FRIB decay station [92].

4. Summary — conclusions

While the quest for understanding the origin of heavy elements in the Universe has been puzzling nuclear physicists and astrophysicists alike for decades, the recent discovery of GW170817 gave the field a major breakthrough. The plethora of electromagnetic and gravitational wave signals offered a new set of observables that r-process models need to explain and reproduce. However, our ability to interpret and reproduce these observables is hindered by the lack of nuclear physics data. r-process abundance calculations are strongly dependent on uncertainties in nuclear masses, β-decay properties and neutron-capture rates. It is therefore of paramount importance to measure the relevant quantities, and to constrain the theoretical models in order to accurately predict r-process abundance distributions. In addition, the same nuclear properties and in addition atomic properties are needed to interpret the observed kilonova signals, and to extract information about the participating isotopes, since the signals themselves are strongly Doppler shifted and impossible to explain without accurate nuclear input.

The rare isotope experimental community has focused on measuring the required nuclear properties for decades. However, with limited access to the relevant r-process isotopes, the uncertainties are still significant. Building on the expertise and knowledge of current radioactive beam facilities, several facilities are currently planned or are under construction around the world. The Facility for Rare Isotope Beams, FRIB, in the US will offer access to most of the isotopes that drive the r process, dramatically increasing our knowledge on the properties of neutron-rich rare isotopes. Combined with state-of-the-art equipment, FRIB will allow the measurement of the required nuclear properties, offering a new breakthrough to our understanding of r-process nucleosynthesis, coming this time from the nuclear physics side.

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