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Review

Current status of r-process nucleosynthesis

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ABSTRACT

The rapid neutron capture process (r process) is believed to be responsible for about half of the production of the elements heavier than iron and contributes to abundances of some lighter nuclides as well. A universal pattern of r-process element abundances is observed in some metal-poor stars of the Galactic halo. This suggests that a well-regulated combination of astrophysical conditions and nuclear physics conspires to produce such a universal abundance pattern. The search for the astrophysical site for r-process nucleosynthesis has stimulated interdisciplinary research for more than six decades. There is currently much enthusiasm surrounding evidence for r-process nucleosynthesis in binary neutron star mergers in the multi-wavelength follow-up observations of kilonova/gravitational-wave GRB170807A/GW170817. Nevertheless, there remain questions as to the contribution over the history of the Galaxy to the current solar-system r-process abundances from other sites such as neutrino-driven winds or magnetohydrodynamical ejection of material from core-collapse supernovae. In this review we highlight some current issues surrounding the nuclear physics input, astronomical observations, galactic chemical evolution, and theoretical simulations of r-process astrophysical environments with the goal of outlining a path toward resolving the remaining mysteries of the r process.

Contents

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1. Introduction

The origin of most atomic nuclei with masses above that of iron group elements (as well as some lighter elements) is attributed to neutron capture nucleosynthesis. Two different categories for neutron capture have been identified, depending upon the competition between neutron capture and β decay: If neutron capture rates are slow compared to β decay rates, only isotopes near stability are synthesized. This has been termed the slow-neutron capture process, or *s process* [1,2].

On the other hand, when neutron captures occur much more rapidly than β-decay rates, isotopes far from stability are synthesized. This is called the rapid-neutron capture process, *r-process* [1], or *fast* [2] process. Successive and rapid neutron capture on a particular element can build up neutron-rich isotopes to the point at which photo-disintegration reaction rates equal those of neutron capture. At this point $(n, \gamma) \leftrightarrows (\gamma, n)$ equilibrium is maintained until the waiting-point isotope can β decay to the next element. This process of neutron capture and β decay then repeats along a reaction path far from stability. This is called the *r-process path*. It is described in more detail in Section 6.

From the effect of nuclear closed shells on the final r-process abundances, one can deduce that the r-process path runs far from the line of nuclear stability, so that very high neutron fluxes must occur. Moreover, because of the short β-decay times far from stability, the process only requires a short duration, typically tens of seconds or less to synthesize nuclei all the way from the iron group to actinide elements.

One way of regulating the r process is via fission recycling. As neutron captures and β decays proceed to the heaviest nuclei, eventually the r process is terminated by neutron-induced or β-induced fission. The two fission fragments with intermediate-masses $120 \lesssim A \lesssim 160$ can then continue to undergo neutron captures and β decays. This re-cycles the r process, and the repeated flow through the entire r-process path results in a reduced dependence on the astrophysical environment. This enhances the importance of nuclear properties for determining the isotopic abundances.

The s-process, on the other hand, can occur with comparably low neutron fluxes inside stars. This process is generally associated [3] with episodic neutron irradiation of pre-existing nuclear matter in stars during the asymptotic giant branch stage of stellar evolution.

The nuclear physics and astrophysics for s-process nucleosynthesis are more accessible both experimentally and theoretically than that for the isotopes relevant to the r process. Therefore, one typically evaluates the s-process nucleosynthesis in the solar system abundances and subtracts them from the total of the heavy-element abundances, to deduce the solar r-process abundance distribution; this is described below in Section 5.

An important stimulus for studies of the r process has been the elemental abundance pattern seen in spectroscopic studies of emission from the stellar-atmospheres of metal-poor stars in the Galactic halo. Such stars occasionally exhibit the same elemental r-process abundance pattern as known from the solar system abundances, This pattern appears to be rather universal even for stars at much younger ages and metallicities than the Sun. Even though the iron content, as a proxy for metallicity, varies over orders of magnitude, this elemental abundance pattern is rather robust for elements in the range of $Z = 50$–75 [e.g. 4,5]. Thus, the enrichment from the r process appears to have occurred very early in the cosmic chemical evolution of the Galaxy. Moreover, it appears to have operated the same way as it did to produce the solar abundances attributed to the r process. These observational facts suggest a rather well-regulated origin of heavy elements beyond iron. However, we do not know if this may be only an artifact of nuclear properties such as binding energies and β-decay rates, or it may point to a single cosmic site with astrophysical conditions that are generated uniformly throughout cosmic time.

There appears to be a relatively large scatter of abundances at low metallicities compared to the light α-elements produced in supernovae. This indicates that such r-process nucleosynthesis events may be attributable to only one or very few events, and that these events are rather rare compared to occurrence rate of supernovae.

The absolute abundances of r-process elements are about seven orders of magnitude below those of abundant elements such as C and O. Therefore, with a galactic total interstellar gas mass estimate of $\sim 10^{10}$ $M_{\odot}$ [6], the total amount of r-process material in the Galaxy is of order a few hundreds of $M_{\odot}$. Therefore, nucleosynthesis events at occurrence rates of 10^{-4} y^{-1} or below, ejecting amounts of 10^{-4} $M_{\odot}$ or more are sufficient sources for the r process.

From a theoretical astrophysics point of view, a variety of sources have been proposed that can provide the required conditions of high neutron flux during a short time. Among these are core collapse supernovae which form a proto-neutron star after collapse. This nascent neutron star provides a plausible environment for the generation of the requisite high neutron fluxes. In such a final stage of stellar evolution, the stellar core that has transformed its composition during different nuclear burning stages in the previous massive-star evolution collapses when further nuclear energy release is impossible. This may occur as the composition has evolved to iron for more-massive stars ($>$11–25 $M_{\odot}$), or from electron captures de-stabilizing a degenerate core of O-Ne-Mg composition for stars with $m \sim 8$–10 $M_{\odot}$. The details of matter flows near a newly-formed neutron star, however, are complex, and neutrino interactions, hydrodynamic convection, and magnetic fields are among the challenging issues to affect the outcomes. Rare scenarios such as rapidly rotating cores with high magnetic fields may be required to generate significant amounts of r-processed ejecta as described in Section 6.

Another plausible scenario is the disruption of neutron stars, either in a collision with between two neutron stars or a neutron star plus a black hole, or from matter accretion onto a black hole, around which an extremely-compact accretion disk forms. Here again extreme nucleosynthesis and neutron rich conditions are expected.

A third alternative that has been proposed is the efficient production of neutrons in explosive helium burning. Although this scenario seems no longer viable for the main r process, it may be a source for the light-element primary process *LEPP* [7].

During the last decades, astronomical observations have become sufficiently detailed to show that there is more complexity in the above-described picture: The s process itself was found to show a cosmic evolution that includes puzzles, as, for example, is evident in the C enhancements of very metal poor stars or in globular cluster metallicities. Hence, nuclei which are not due to the s-process are not necessarily due to a single r process. Variability studies for r-process evolution have indicated that there are differences between the observed abundances of less massive and the most-massive elements. This suggests a distinction of a *main*, and *weak*, and possibly an *intermediate* r process, which are independently supported by theoretical modeling of the sources. It is tempting to associate each of these to a particular and specific type of source.

Chemical evolution studies have shown that each of the above candidate r-process sources has specific issues to consistently explain the observed abundance evolution. Enrichments with the typical r-process abundance pattern have been found at lowest metallicities. This suggests that the r-process events should be linked rather promptly to star formation, and not have a significant delay in ejecting their nucleosynthesis yields (as expected for all kinds of binaries involving a compact star remaining after stellar evolution has ended, as, for example, in type Ia supernovae, or neutron star mergers). Constraining the early evolution of interstellar gas composition, and matching such delay constraints after the onset of star formation, could help to identify the type of sources [e.g. 8–10]. This has been a major challenge, in particular not only for the neutron star merger source, but also even for core collapse supernovae. Suggestions have been made [e.g. 11] for a multi-component origin of the r process, based on neutron star mergers as a dominating source, but supplemented by variants of core collapse environments that added just what was difficult to obtain from the neutron star merger model. It remains to be seen if such a hybrid model, with its larger number of degrees of freedom, can be sufficiently constrained by observation and theory to provide a firm and satisfactory explanation of r-process nucleosynthesis in the Galaxy.

After decades of investigating different aspects of core collapse supernovae as potential sites for the r process, it is now thought that it is difficult to find the right conditions in this environment. In particular, the conditions of neutron richness in the neutrino-driven wind [12] may revert into proton richness once neutrino (and antineutrino) interactions are accounted for in detail as described in Section 6. Hence, only a weak r process might occur in this environment.

The collision of two neutron stars, also called *merger* event, was recognized 40 years ago as a promising scenario, with ejection of enough matter from nucleosynthesis to consider those events as significant contributors to the cosmic abundance of r elements [13]. With the discovery of a binary neutron star merger through gravitational waves in 2017 [14], the hypothesized occurrence of neutron star mergers now also is an observational fact. From the astronomical signature of this event in electromagnetic emission, the *macronova* or *kilonova* associated with the neutron star merger (see Metzger [15], and references therein, for a review of kilonovae) adds a significant advance in the quest for the origins of the r-process abundances. From the duration of the electromagnetic emission, it was clear that some injection of energy was powering the kilonova emission, radioactivity from nucleosynthesis being the most plausible. Then the optical/IR spectra of the emission peak in the IR also suggested that atoms heavier than iron are responsible for the absorption and re-radiation of the emission from this interior energy source. Clearly, this single event matches all expectations for neutron star collisions contributing to cosmic r-process nucleosynthesis. The current consensus is that the *main/heavy* r process may be linked to neutron star merging, while the *light/weak* r process may be realized in neutrino driven winds from core collapse supernovae [11].

Studies of the r process have brought together nuclear physicists, astronomers and astrophysicists under a common theme. Even though it addresses only the origin of elements heavier than iron, whose abundances altogether are about 5 to 8 orders of magnitude below those of lighter cosmic nuclei, the attempts to understand the sites and physics of the r process are still among the main drivers of the entire field of nuclear astrophysics. In this review, we begin by laying out the constraints on nuclear reactions from nuclear properties and theory. We show how nuclear experiments can continue to place the nuclear physics input for the r process on a firm basis. This puts us in a position to present the candidate sources that may implement conditions for such nuclear reactions. Then we review the astronomical observations as they now constrain the r-process origins that we wish to model and explain. After this, we review and discuss the variety of models for the candidate sources in detail. This includes the nucleosynthesis within a source, the astrophysics including processes and the rates of occurrence, and their observational support in terms of direct source observations and less direct abundance histories. We conclude with a critical discussion of the achievements, status and prospects to solve the quest for the cosmic origins of the heaviest elements and isotopes in the r process.

2. Nuclear theory

Theoretical calculations of the r-process nucleosynthesis yields provide crucial information not only to identify its sites, but also to interpret observations. Nuclear network calculations are not yet at a stage of precision for a comprehensive comparison with the observations. In principle, these network calculations involve a very large number of nuclei ranging from the line of stability to the neutron drip line. It is presently impossible to measure reaction rates and nuclear properties for all these nuclei. Hence, one needs reliable theoretical estimates of their properties. Excellent reviews of the nuclear theory issues in r-process nucleosynthesis are available [16,17], so that here we only summarize some salient points.

Nuclear physics input into the network calculations include nuclear masses, β-decay properties, as well as neutron capture and fission rates. Theoretical approaches to each of these are summarized briefly here.

2.1. Theoretical neutron capture rates

The nuclear reaction flow in the r process occurs in the vicinity of the neutron drip line. There are two main theoretical approaches for neutron capture reactions. These are: (1) via a compound nucleus (including resonances) as in the Hauser–Feshbach estimates; (2) direct capture and semi-direct (DSD) processes. For most applications of r-process nucleosynthesis, nuclear cross sections have been based upon a simple estimate of the direct and semi-direct cross sections in terms of pre-equilibrium γ emission [18], or in the context of Hauser–Feshbach theory [e.g. 19–22]. Such an approach can be justified when it is applied to nuclei in the vicinity of the stability line. However, in the neutron-rich region relevant to the r process, the neutron separation energies are diminished, so the compound nuclei may not have enough level density to compete with the compound elastic process. In this case, the compound capture cross section may be suppressed, and direct capture becomes dominant even at low energies.

Normally, the direct process is not very important because its cross section is much smaller than the compound capture cross sections. However, in Mathews et al. [23] it was noted that far from stability where the level density is low, the direct capture process could be the dominant mode of neutron capture reactions for the r process.

In Chiba et al. [24] the DSD components of the neutron capture cross sections were calculated for a number of tin isotopes by employing a single-particle potential (SPP) that gives a good reproduction of the known single-particle energies (SPEs) over a wide mass region. The results were compared with the Hauser–Feshbach contribution in the energy region of astrophysical interest. Their calculations showed that the Hauser–Feshbach component drops off rapidly for the isotope ^{132}Sn and toward more neutron-rich nuclei, whereas the DSD component decreases gradually and eventually becomes the dominant reaction mechanism. In Chiba et al. [24] the reason for the difference in the isotopic dependence between the Hauser–Feshbach and DSD components was discussed, and its implication for r-process nucleosynthesis was given.

This result is consistent with those of previous studies, but the dependence of the DSD cross section on the target mass number is a feature of their SPP that gave a smooth variation of SPEs. As a consequence, the direct portion of the DSD components gave the largest contribution to the total (n, γ) cross section for neutron-rich isotopes below a few MeV, and the direct capture process modifies significantly the astrophysical (n, γ) reaction rates. The semi-direct component, however, gives a negligible contribution to the astrophysical reaction rates, but its impact is significant above several MeV.

Valuable studies of the impact of varying theoretical neutron capture rates in r-process models can be found in Mumpower et al. [16]. In those studies, a Monte Carlo variation of Hauser–Feshbach neutron capture rates within the context of several mass models was explored. Crucial isotopes in the vicinity of the r-process peaks at $A = 130$ and 195 were identified and also in the vicinity of the rare-earth peak whose measurement would be most effective in reducing the uncertainties in r-process abundance calculations.

2.2. Theoretical nuclear masses

Experimentally determined masses [25–27] should be adopted if available. Otherwise, the theoretical predictions for nuclear masses are necessary. At present there are many available theoretical mass estimates far from stability. A good resource for nuclear masses can be found at http://nuclearmasses.org.

For nuclear masses there are two basic theoretical approaches: either models which combine liquid-drop model with the nuclear Shell Model and pairing corrections, or models which are entirely microscopic. A review of these different approaches is given in Lunney et al. [28] and in Kajino and Mathews [17]. Different nuclear mass models vary in their success in describing experimentally known nuclear masses [29]. Hence, a comprehensive study of the sensitivity of r-process nucleosynthesis to individual nuclear masses was carried out in Mumpower et al. [30]. It was found that mass variations of ± 0.5 MeV can result in up to an order of magnitude change in the final abundance pattern. A more recent calculation using 10 different mass models found a similar sensitivity [31]. It is worth emphasizing that nuclear masses enter into the calculations of all other quantities relevant to the r process.

Theoretical mass tables for r-process nuclei are based upon macroscopic/microscopic methods depending upon a liquid droplet formula plus shell corrections. The most popular adaptation of this is the finite range droplet model (FRDM) [32, 33]. Another variant of the macroscopic/microscopic approach is the phenomenological hybrid KTUY model [34,35]. A third is the DZ model [36] based upon a parametrization of multipole moments of the nuclear Hamiltonian. In a sense the DZ is more fundamental than the macroscopic/microscopic models. However, it is not strictly a microscopic theory, since no explicit nuclear interaction appears in the formulation.

At the next level would be masses based upon the extended Thomas–Fermi random phase approximation (ETSFI) plus Strutinsky integral semi-classical approximation to a Hartree–Fock (HF) approach [37,38]. The most microscopic extrapolations generally available of masses for neutron rich nuclei are those based upon the Skyrme Hartree–Fock–Bogoliubov (HFB) method. This is a fully variational, approach with single-particle energies and pairing treated simultaneously and on the same footing. Some recent formulations include: HFB-19, HFB-21 [39]; Gogny HFB [40]; the Skyrme-HFB [41,42]; HFB-15 [43]; HFB-14 [44].

A good comparison of the relative merits of each approach can be found in Pearson and Goriely [45]. All approaches give a reasonable fit to known nuclear masses. However, there can be large deviations as one extends the mass tables to unknown neutron rich nuclei. Hence, there is a need for experimental mass determinations for neutron rich nuclei.

A recent study has been made [46] of the impact of nuclear mass uncertainties based upon six Skyrme energy density functionals based on different optimization protocols. Uncertainty bands related to mass modeling for r-process abundances were determined for realistic astrophysical scenarios. This work highlights the critical role of experimental nuclear mass determinations for understanding the site for r-process nucleosynthesis.

2.3. Theoretical nuclear structure

The level structure of nuclei along the r-process path is important both as a means to determine the partition functions and as a means to test the strength of shell closures. Recently a number of studies have been completed [47–49] in the neighborhood of the $N = 82, A = 130$ r-process peak. In particular, the first ever studies [47] of the level structure of the waiting-point nucleus ^{128}Pd and ^{126}Pd have been completed. That study indicated that the shell closure at the neutron number $N = 82$ is fairly robust. Hence, there is conflicting evidence between the nuclear masses and nuclear spectroscopy as to the degree of shell quenching near the $N = 82$ closed shell. It will be important to clarify this point as it has important implications for the site of r-process nucleosynthesis as discussed below.

2.4. Theoretical β-decay rates

Treating β-decay properties for a wide range of nuclei using a single model is not an easy task. The so-called gross model was originally introduced to take both allowed and first-forbidden transitions into account by introducing certain approximations such as replacing sums by integrals and assuming average values of matrix elements [50,51]. This theory is further refined by introducing shell effects of the parent nuclei [52]. At present, a popular alternative is the quasi particle random-phase approximation for the Gamow–Teller matrix elements [53]. Neutron capture cross sections are calculated using the Hauser–Feshbach statistical model, again necessitating theoretical input for the level densities and gamma-strength functions for the experimentally inaccessible neutron-rich nuclei.

The β-decay rates, particularly at waiting point nuclei, constitute one of the most important nuclear physics inputs to nucleosynthesis calculations in the r process. Theoretical investigations of the β decay of isotones with neutron magic number of $N = 82$ have been done by various methods including the shell model [54], quasiparticle random-phase approximation (QRPA)/finite-range droplet model (FRDM) [55], QRPA/extended Thomas–Fermi plus Strutinsky integral (ETFSI) model [56], and Hartree–Fock–Bogoliubov (HFB) + QRPA [57] calculations as well as in the continuum quasiparticle random-phase approximation (CQRPA) [58]. The half-lives of nuclei obtained by these calculations are rather consistent with one another, and especially in shell-model calculations experimental half-lives at proton numbers $Z = 47$, 48, and 49 are well reproduced [59].

For the β decays at $N = 126$ isotones, however, half-lives obtained by various calculations differ from one another [60,61]. First-forbidden (FF) transitions become important for these nuclei in addition to the Gamow–Teller (GT) transitions in contrast to the case of $N = 82$.

A strong suppression of the half-lives has been predicted in [58] for $N = 126$ isotones due to the FF transitions. Most shell-model calculations of the β-decay rates of $N = 126$ isotones have been done with only the contributions from the GT transitions included [60,62]. Moreover, as noted below experimental data for the β decays in this region of nuclei are not yet available. The region near the waiting point nuclei at $N = 126$ is therefore called the "blank spot" region.

Suzuki et al. [63] have studied β decays of $N = 126$ isotones by taking into account both the GT and FF transitions to evaluate their half-lives. Shell-model calculations were done with the use of shell-model interactions based upon modified G-matrix elements that reproduce well the observed energy levels of the isotones with a few (two to five) proton holes outside ^{208}Pb [64,65].

The impact of first-forbidden transitions on decay rates was studied by Marketin et al. [66] using a fully self-consistent covariant density functional theory (CDFT) framework to provide a table of β-decay half-lives and β-delayed neutron emission probabilities, including first-forbidden transitions. This work demonstrated that there is a significant contribution of the first-forbidden transitions to the total decay rate of nuclei far from the valley of stability. This also leads to better agreement with experimentally determined half lives as discussed below.

In addition to ground state β decay, at the high temperatures of the r-process environment decay can proceed through thermally excited states. A calculation was made by Famiano et al. [67] to evaluate the possible effects of the β decay of nuclei in excited-states on the astrophysical r process. Single-particle levels were calculated in the FRDM with quantum numbers determined based upon their proximity to Nilsson model levels. The resulting rates were used in an r-process network calculation. Even though the decay rate model was simplistic, this work did provide a measure of the possible effects of excited-state β decays on r-process freeze-out abundances. The main result was that in the more massive nuclei, the speed up of the decay rates in the approach to closed shells tends to exaggerate the underproduction of nuclei below the nuclear closed shells as discussed below.

2.5. β-delayed neutron emission

Beta-delayed neutron emission is particularly important for the freezeout of the r process. Recently, beta-delayed neutron emission probabilities of neutron rich Hg and Tl nuclei have been measured [68] together with β-decay half-lives for 20 isotopes of Au, Hg, Tl, Pb, and Bi in the region of neutron number $N \geq 126$. These are the heaviest nuclear species for which neutron emission has been observed.

Although not directly on the r-process path, these measurements have provided information with which to evaluate the viability of nuclear microscopic and phenomenological models for the high-energy part of the β-decay strength distribution. Indeed, this study indicated that there is no global β-decay model that provides satisfactory β-decay half-lives and neutron branchings on both sides of the $N = 126$ shell closure. There was, however, a slight preference for the Hartree–Fock–Bogoliubov model of Marketin et al. [66].

2.6. Fission barriers and fission fragment distribution

Fission is another important component of the r process. During the evolution of the system along the r-process path there can be multiple fission cycles. Once this path reaches fissionable nuclei the resulting fission products continue capturing neutrons, potentially repeating the cycle a number of times [69,70]. The relevant fission cross sections are not yet experimentally accessible, requiring theoretical input. Fission may also be β-delayed: a parent nucleus first β decays into a daughter nucleus which then undergoes fission. Beta-delayed fission may be a dominant fission channel in the termination of the r process [11,71].

In r-process models with a very high neutron-to-seed ratio (such in the ejecta from neutron star mergers) the r-process path can proceed until neutron-induced or beta-induced fission terminates the beta flow at $A \sim 300$. Determining where this occurs can significantly impact the yields from r-process models [11,72]. Unfortunately there are no measurements of fission barriers or fission fragment distributions (FFDs) for nuclei heavier than ^{258}Fm [73].

This is a major uncertainty in all calculations of fission recycling in the r process [11]. Shibagaki et al. [11] considered a FFD model based upon the KTUY model plus a two-center shell model to predict both symmetric and asymmetric FFDs with up to three components. As such, fissile nuclei could span a wide mass range (A = 100–180) of fission fragments as demonstrated below.

On the other hand, the r-process models of Korobkin et al. [74] were mostly based upon a simple two fragment distribution as in Panov et al. [75] (or alternatively the prescription of Kodama and Takahashi [76]). The assumption of only two fission daughter nuclei tends to place a large yield near the second r-process peak leading to a distribution that looks rather more like the solar r-process abundances. In contrast, the FFDs of Goriely et al. [77] are based upon a rather sophisticated SPY revision [78] of the fission model of Wilkins et al. [79]. The main ingredient of the that the individual potential of each fission fragment is obtained as a function of its axial deformation from tabulated values. Then a Fermi gas state density is used to determine the main fission distribution. This leads to FFDs with up to four humps.

An even more important aspect is the termination of the r-process path and the number of fissioning nuclei that contribute to fission recycling and the freezeout of the r-process abundances. The r-process path in Shibagaki et al. [11] proceeded rather below the fissile region until nuclei with $A \sim 320$, whereas the r-process path in Goriely et al. [77] terminates at $A \approx 278$ [or for a maximum $\langle Z \rangle$ as in Korobkin et al. [74]]. Moreover, in Shibagaki et al. [11] it was found that only ∼10% of the final yield comes from the termination of the r-process path at N = 212 and Z = 111, while almost 90% of the $A = 160$ came from the fission of more than 200 different parent nuclei mostly via beta-delayed fission. On the other hand, the yields of Goriely et al. [77] that are almost entirely due to a few $A \approx 278$ fissioning nuclei with a characteristic four hump FFD. As noted below, this has a dramatic impact on the final r-process abundance distribution.

Recently, there has been significant progress by the FIRE collaboration. In Vassh et al. [80] results were compared using the Finite Range Droplet Model, Thomas–Fermi (TF), Hartree–Fock–Bogoliubov (HFB-17), and Extended Thomas–Fermi with Strutinsky Integral (ETFSI) model masses and corresponding barriers along with the phenomenological fission yields described in that work. In particular, they explored how the different termination points for the r process predicted by these models influence the final abundance pattern, and they identified which fissioning nuclei were most accessed in neutron-star merger conditions.

Similarly, in Mumpower et al. [71] an exploration of the impact of beta-delayed fission in the r-process in the tidal ejecta of neutron-star mergers was made. This study showed that beta-delayed fission is a key fission channel that shapes the final abundances near the second r-process peak.

2.7. Neutrino physics

One common element for all possible r-process sites is the presence of an abundant number of neutrinos, making neutrino interactions a crucial part of the nuclear physics input. Since neutrinos only interact via weak interactions they can transfer energy and entropy over long distances. In addition, charged-current interactions affect the neutron-to-proton ratio in the r process. This implies that fundamental neutrino parameters such as the neutrino mass hierarchy, mixing angles and the possible existence of sterile neutral fermions which mix with the neutrinos but do not take part in the weak interactions can influence r-process nucleosynthesis. To illustrate how neutrinos impact element synthesis consider the mass fraction of the species i in the nucleosynthesis environment:

$$X_i = \frac{N_i A_i}{B} \tag{1}$$

where N_i is the number of species i per unit volume, A_i the atomic weight of these species, and

$$B = \sum_j N_j A_j \tag{2}$$

is the total baryon number. If the medium is locally charge neutral the electron fraction is given by

$$Y_e = X_p + \frac{1}{2} X_\alpha + \sum_{h \neq p,\alpha} \left(\frac{Z_h}{A_h} \right) X_h \tag{3}$$

where Z_h is the charge of the nucleus h. Note that X_h for the heavier nuclei is exceedingly small. The rate of change of the number of free protons is given by

$$\frac{dN_p}{dt} = -\lambda_- N_p + \lambda_+ N_n \tag{4}$$

where λ_- is the total rate for the reactions $\overline{\nu}_e + p \to n + e^+$ and $e^- + p \to n + \nu_e$ which destroys protons and λ_+ is the total rate for the reactions $\nu_e + n \to p + e^-$ and $e^+ + n \to p + \overline{\nu}_e$ which creates protons.

In writing Eq. (4) one assumes that neutrinos do not dissociate alpha particles and ignores spallation reactions on heavier nuclei which could knock out nucleons in the earlier stage of nucleosynthesis. This is known as the α process, and occurs prior to the neutron-capture flow followed by subsequent β decays. Both are reasonable approximations given that the peak of the neutrino energy spectra during the r process occurs at energies well below the alpha particle binding energy and spallation thresholds for most heavier nuclei. However, refer to Meyer [81] and Terasawa et al. [82] and the discussions in Section 6.1 for more details about the effects of dissociation and spallation reactions on alpha particles and heavier nuclei which we ignore in the present discussion.

From Eqs. (3) and (4) we can write the equilibrium value of the electron fraction approximately as

$$Y_e = \frac{\lambda_+}{\lambda_- + \lambda_+} + \frac{1}{2} \frac{\lambda_- - \lambda_+}{\lambda_- + \lambda_+} X_\alpha + \sum_{h \neq p,\alpha} \left[\left(\frac{Z_h}{A_h} \right) - \frac{\lambda_+}{\lambda_- + \lambda_+} \right] X_h. \tag{5}$$

Hence the electron fraction in the nucleosynthesis environment is primarily determined by the neutrino reaction rates. These rates in turn are determined by the neutrino cross sections and neutrino fluxes for the appropriate flavors:

$$\lambda = \int dE_\nu \, \sigma(E_\nu) \frac{d\Phi_\nu}{dE_\nu}. \tag{6}$$

The fundamental neutrino properties such as the masses and mixing angles determine the flavor content of the neutrino energy spectrum which then determines the value of the electron fraction, the controlling parameter of the r process [83]. In many astrophysical environments the sheer number of neutrinos produced necessitate including neutrino–neutrino interactions in the neutrino transport and the resulting collective neutrino oscillations [84–88]. It should also be kept in mind that neutrinos can also induce fission during the r process [89,90].

3. Experimental nuclear data

Because the r-process environment is so closely linked to the properties of the nuclei involved, an understanding of nuclear properties is necessary. Nuclear physics properties necessary to understand the production of nuclei in an r-process site include neutron separation energies, S_n; β-decay rates λ_β; neutron capture rates, λ_n; and information on the shell structure of r-process nuclei [91]. While many of the properties of r-process progenitor nuclei have yet to be measured, studying neutron-rich nuclei approaching the r-process path is beneficial as it provides constraints on nuclear structure models used to extrapolate the properties of r-process nuclei.

From an astronomical standpoint, an understanding of the r process arises from observations of visible light absorption spectra from stars containing r-process elements [92,93], γ-ray observations [94,95], and gravitational wave observations [96]. All of these observations are used to constrain a different aspect of the r process including yields and the nature of the actual r-process site. Observational data is also intertwined with nuclear data. Both aspects of r-process research rely heavily on each other. For this reason, accurate, thorough, and useful nuclear data are important.

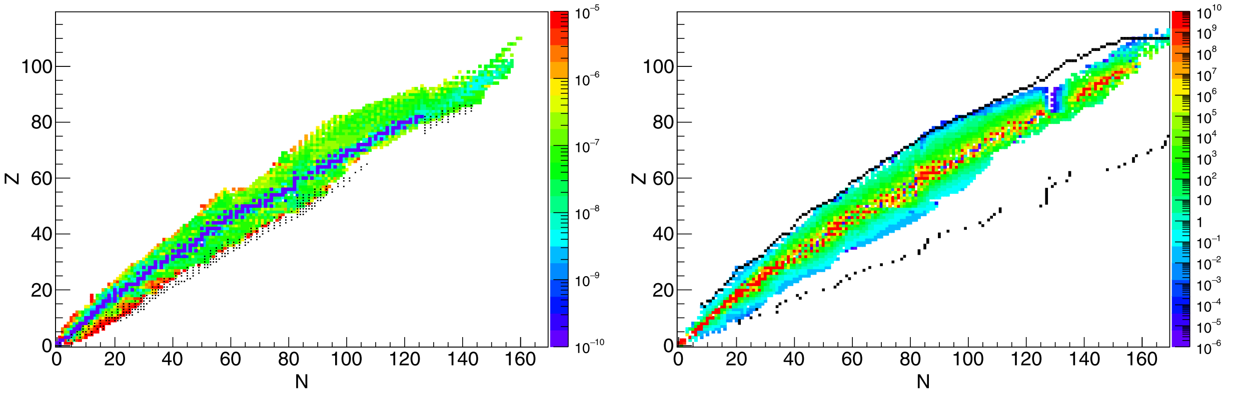

Fig. 1. Left: Relative uncertainties δm/m of nuclear measured nuclear masses. Right: Measured decay half lives (in s) of nuclei. The approximate location of the r-process path is shown on the left diagram, and the approximate locations of the neutron and proton drip lines are shown on the right figure.

3.1. Nuclear masses

Perhaps most fundamental to understanding the r process is a knowledge of nuclear masses. Knowing nuclear masses of neutron-rich nuclei can allow a determination of neutron separation energies, S_n, which will lead to a determination of the classical r-process path as a function of environmental neutron abundance and temperature. Further, nuclear mass measurements can help to constrain models, which are generally used to extrapolate to the neutron-rich nuclei [97].

Detailed mass systematics toward the r-process path is necessary to constrain the uncertainties associated with the r-process evolution and final abundance distribution [46,98,99]. As the hot r-process environment is presumed to start at a temperature $T_9 \approx$10 and proceed to form light nuclei at about $T_9 \approx$2.5 (where $T_9 \equiv 10^9$ K) followed by the formation of the heavier nuclei before finally freezing out at $T_9 \approx 1$, it is worthwhile to measure nuclear masses to an uncertainty of $\delta m \lesssim kT \approx 100$ keV. However, even uncertainties of several hundred keV are useful as they can help constrain mass models. Likewise, masses of neutron-rich nuclei that approach – but are not on – the r-process path are also useful for constraining mass model trends.

Given the number of techniques and efforts to measure nuclear masses with greater precision, constraints on nuclear masses and mass models for nuclei approaching the r-process path have seen significant progress in the past decade. A representation of the relative uncertainty in nuclear mass measurements as of the AME2016 update is shown in Fig. 1. While the masses of most r-process nuclei have yet to be studied, progress continues to be made.

Direct measurements of nuclear masses include frequency-based and time-based measurement [100,101]. Of the frequency-based measurements, Penning traps (which fuction by measuring the components of the cyclotron frequency of an ion in a magnetic field) and storage rings are the most developed and well-known techniques. Time-of-flight (TOF) measurements vary in technique, but all rely on measuring the flight time of nuclei of unknown mass between two points in a beam path of known rigidity and comparing to that of nuclei for which the masses are known. Each technique has its own advantages and disadvantages. Mass measurement techniques are limited by the half-lives of nuclei they are capable of measuring. Likewise, each technique has a mass resolution limit. The approximate range of lifetimes and mass resolutions accessible by various techniques is shown in Fig. 2.

Current direct mass measurement techniques have been limited primarily by the production rates of nuclei to be measured. While the masses of several r-process progenitor nuclei have been measured by facilities such as the Canadian Penning Trap (for example) [103–105], with newer facilities, such as the RIBF and FRIB, it will be possible extend the reach of current measurements to include more or all of the r-process nuclei. Various mass measurement techniques and recent results from selected facilities are described below.

3.1.1. Mass measurement compilations and evaluations

The field of measuring nuclear masses directly and indirectly is rapidly changing with multiple measurements made yearly. While mass measurement techniques and programs are described below with some notable recent measurements, multiple mass evaluations and compilations are available and described for recent updates.

The Atomic Mass Evaluation was recently updated (AME2016) [106,107] to replace the 2003 version (AME03) [26, 108,109]. This volume also contains the NUBASE2016 tables [106,107,110] which contain recommended experimentally known and extrapolated properties. This evaluation includes complete experimental information as well as evaluation procedures and descriptions of calculated data. Recommended values are reported. Downloadable tables for the NUBASE2016 database are available at multiple online sites [111,112].

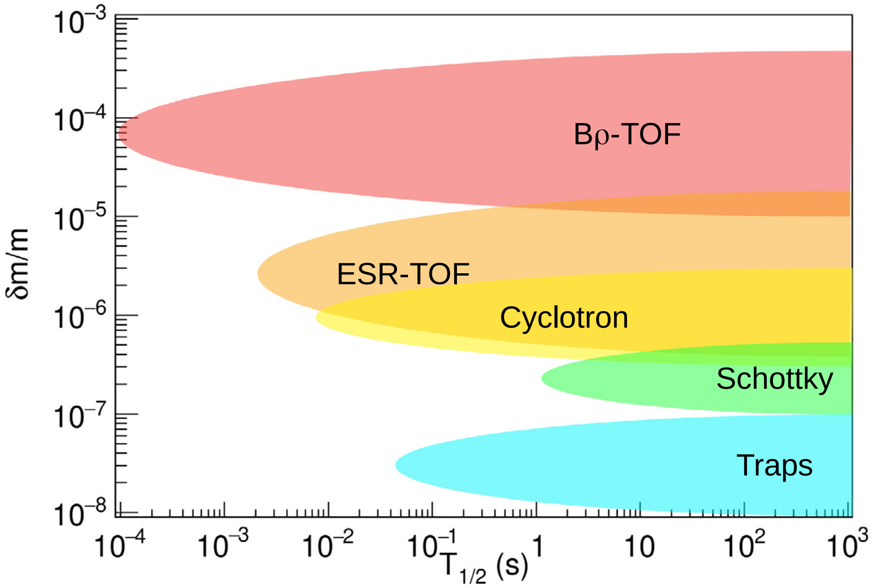

Fig. 2. Schematic of approximate resolutions and lifetimes of various mass measurement techniques [102].

In addition, the Atomic Mass Compilation 2012 (AMC12) [113] provides an extensive list of experimental and calculated masses. This reference could be useful as it also provides in the tabulation the experimental facility that produced the listed results. Comparisons between AMC12 and the AME03 have also been noted [114].

Multiple online resources are also available, including `nuclearmasses.org` [115] and the National Nuclear Data Center (NNDC) [116]. The former provides an interface for examining nuclear properties from multiple datasets. Another useful feature of `nuclearmasses.org` is an up-to-date compilation of new mass measurements. The NNDC provides access to multiple reaction and structure databases, as well as interfaces to access nuclear properties in the Evaluated Nuclear Structure Data File (ENSDF).

3.1.2. Trap measurements

Measurements using Penning traps are capable of very fine mass resolution on the order of $\delta M/M \sim 10^{-9}$. They are, however, limited in the lifetimes of the nuclei that can be studied with these techniques. Because the trap must maintain the captured nuclei long enough to measure it, lifetimes of nuclei measured with Penning traps are limited to the order of milliseconds.

Several trap facilities around the world have measured to extremely good accuracy the masses of several proton-rich and neutron-rich nuclei. While the number of nuclei along the r-process path which have been measured using Penning traps is limited, masses approaching the r-process path are still useful as they can be used as calibration masses for other techniques which are able to reach more exotic nuclei.

A thorough review of mass measurements with Penning traps is given in Dilling et al. [117].

JYFLTRAP. The JYFLTRAP facility is a double cylindrical Penning trap installed at the IGISOL facility at the University of Jyväskylä [118–122]. It is capable of measuring atomic masses up to $A = 120$ with accuracies ∼50 keV [123]. The JYFLTRAP system routinely measures mass uncertainties of $\delta m/m \sim 10^{-8}$ [124]. Currently, the JYFLTRAP facility has measured the masses of nearly 300 neutron-rich nuclei and those of nearly 100 proton-rich nuclei [118,125–133]. Of these masses, a portion has been measured near the Z = 50 waiting point of the r process, ^{131}Cd, and neutron-rich Sb and Te. Nuclear masses have also been measured for nuclei near the r-process path for nuclei between the first and second r-process peaks.

ISOLTRAP. The ISOLTRAP facility is a tandem Penning trap mass spectrometer located at the online isotope separator ISOLDE at CERN. The masses of over 400 nuclei have been measured with lifetimes down to ∼50 ms and mass accuracies typically of $\delta m/m \sim 5 \times 10^{-8}$ [134,135]. The trap was recently upgraded by the addition of a multi-reflection time-of-flight mass separator/spectrometer [135]. This addition significantly improves the trap's purification capabilities while also operating as a mass spectrometer. In addition, because of the beam purity achieved by the spectrometer, background-free decay half-lives can be measured at the ISOTRAP facility [136]. A proof-of-principle measurement of the half-life of ^{27}Na was performed using this setup.

The ISOLTRAP facility has measured a wide range of masses of nuclei between ^{17}Ne and ^{232}Ra [137,138]. Near the r-process path, the masses of many nuclei in and surrounding the $A \approx 80$ r-process waiting point have been measured. ISOLTRAP results are also pushing the limits of neutron-rich masses past the Z = 82 shell closure. Recent measurements of $^{129-131}$Cd have shown a 400 keV deviation from prior mass determinations using β-decay data [139]. However, as with many Penning trap measurements, the masses of nuclei along the r-process path remain a challenge outside of N = 82 shell closure.

LEBIT. The Low Energy Beam and Ion Trap (LEBIT) facility is located at the NSCL facility in the USA [140]. Combined with the fragmentation facility at the NSCL, the LEBIT facility can measure the masses of nuclei produced by fragmentation of fast beams. Fragments are then slowed in a gas stopping system. This process avoids any chemistry constraints on the beam and is able to produce exotic beams from a variety of primary beams. The LEBIT facility operates a linear gas stopper and a cyclotron gas stopper [141] along with a laser ablation ion source and a plasma ion source, both used for stable beams. An accumulator and buncher downstream of the gas stoppers and ion sources cools the beam prior to injection into the single Penning trap system [142].

The LEBIT facility has currently measured the masses of over 50 isotopes. Many of these are impossible to produce at ISOL facilities, a distinct advantage of this facility. Currently, the LEBIT facility has concentrated on precision mass measurements of proton-rich nuclei. The completion of the FRIB facility may provide new opportunities for LEBIT [143].

CPT. The Canadian Penning Trap (CPT), located at Argonne National Laboratory near Chicago, IL, is installed on the ATLAS linac facility [103–105]. While a major concentration of the CPT has been on isotopes along the N = Z line, progress has also been made for nuclei approaching the r-process path [105].

The CPT contains a radio-frequency quadrupole (RFQ) trap and a precision Penning trap. Isotopic species are produced in the ATLAS facility and separated in the Enge split-pole spectrograph. A gas cooler and buncher system thermalizes the nuclei prior to injection into the trap. Measurement accuracy has been extended to levels similar to other facilities, $\sim 10^{-8}$.

Recent upgrades of the gas catcher system [144] and the use of a ^{252}Cf source to produce fission fragments have made possible the measurements of the masses of 40 neutron-rich nuclei with $51 \leq Z \leq 64$ [105]. These measurements are useful to constrain mass models for neutron-rich nuclei relevant to the r process. Measurements of Te and Sb along the r-process path were also made.

TITAN. Located at TRIUMF in Vancouver, BC, the TRIUMF Ion Trap for Atomic and Nuclear Science (TITAN) is a system of multiple Penning traps with a charge breeder from an electron beam and associate photon counters for simultaneous decay spectroscopy [145–149]. While the primary purpose of TITAN is determination of the V_{ud} CKM matrix element, it is also used for nuclear mass measurements and nuclear mass model constraints [150].

TITAN is capable of mass measurements of comparatively short-lived nuclei, having measured the mass of ^{11}Li, with $t_{1/2} = 8.8$ ms [151]. Recently, the TITAN facility was used to measure the masses of the neutron-rich nuclei ^{98,99}Rb and $^{98-100}$Sr at high precisions [152]. Such measurements can constrain mass models for masses approaching the r-process path. Near the N = 82 closed shells, the masses of $^{125-127}$Cd have been measured [153].

The TITAN facility recently underwent an upgrade to install charge breeder capabilities in its electron beam ion trap [149]. This results in higher charge states, improving the precision of mass measurements. The TITAN EBIT also utilizes seven Si(Li) detectors to perform in-trap decay spectroscopy [154]. With this setup 511 keV photons from β-particle annihilation of decay products can be detected.

SHIPTRAP. Though the primary concentration of the SHIPTRAP facility is on proton-rich nuclei, it is worth mentioning as this facility has excelled at probing massive nuclei [137], displaying the range of masses accessible by trap facilities. The SHIPTRAP facility at GSI is a two-stage Penning trap system set up for precision measurements of very heavy ions as well as the search for super-heavy elements. Singly-charged ions produced via fusion-evaporation reactions are delivered to the trap from the SHIP facility at about 100 keV/u and thermalized in a helium gas cell. They are then cooled in an RFQ buncher prior to delivery to the trap [155]. SHIPTRAP was designed and developed for the measurements of nuclei with $Z \geq 92$ including the transuranic elements, an uncharted region in the table of the isotopes for mass measurements [156].

Early measurements of ^{147}Ho^{+}, ^{147}Er^{+}, and ^{148}Er^{+} were determined for the first time using SHIPTRAP [157]. Subsequent measurements have concentrated on proton-rich nuclei relevant to the endpoint of the rp-process [158].

3.1.3. TOF Measurements

Nuclear mass measurement techniques via the time-of-flight (TOF) method – though less accurate than Penning traps – can measure the masses of nuclei with shorter half-lives.

The TOF method is used to measure nuclear masses through the measurement of the flight-time of nuclei between two points in a beam facility [97]. Such a method is generally employed at radioactive ion beam facilities in which detectors resembling high-precision beam diagnostic detectors are used to evaluate particle flight times and momentum. With this infrastructure, the TOF is measured using fast detectors placed at two or more points in the beamline. A particular technique, referred to as the $B\rho$-TOF method, is used to measure masses by measuring the particle rigidity, $B\rho$ along with the flight time of species in the beamline. Alternatively, in an isochronous mode, species with higher velocities have a longer flight path resulting in all nuclei with the same mass-to-charge ratio having the same time-of-flight.

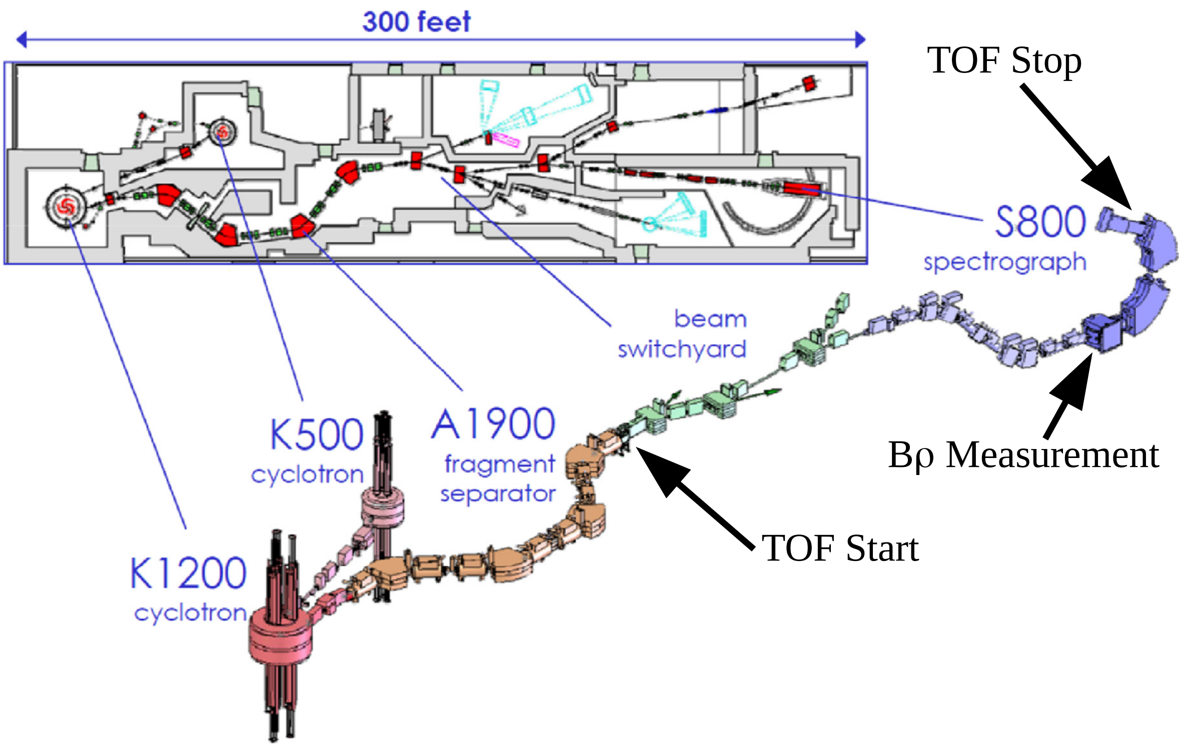

Fig. 3. Schematic of the TOF-Bρ experimental setup at the NSCL facility.

The mass is related to the rigidity and flight time through the relationship:

$$\frac{B\rho}{\gamma} = \frac{mv}{q} \tag{7}$$

where γ is the usual Lorentz factor for particles in the beamline. With an overall TOF uncertainty of $\sim$50 ps (after correcting for path length via a measurement of the particle rigidity), and a TOF $\sim$0.5 μs, the uncertainty in the mass from the TOF is $\sim 10^{-4}$. Greater statistics can reduce the statistical uncertainty to values typically $\sim 10^{-6}$ to $\sim 10^{-5}$. The lifetime limitation of measured nuclei is due to the TOF between two detectors. Calibration of flight times with this method is accomplished by incorporating known "reference masses" in the mixed beam. Because the $B\rho - TOF$ method can measure shorter lifetimes, it can extend the range of known masses to more neutron-rich nuclei. This method is also useful for measuring multiple masses simultaneously in a single experiment.

Reference masses for calibration of the method can be taken from masses measured with Penning traps. The major limitation on nuclei that can be measured is then the production rates of exotic beams. The particle rigidity can be determined by measuring beam position at dispersive planes in the beamline. Additional complications of this method may be the incorporation of charge states (species that are not fully ionized) in the beam, which must be separated by measuring the energy deposition in a particle telescope at the end of the beamline. This method is sometimes referred to as the $B\rho$-TOF-ΔE method.

The resolution of the TOF-$B\rho$ method is generally $\sim$100 keV/c^2, which is roughly the temperature, kT, of the r-process environment. This resolution is generally sufficient to constrain mass models far from stability.

Mass measurements at facilities incorporating the $B\rho$-TOF or $B\rho$-TOF-ΔE method are described below.

NSCL. At the time of this writing, the National Superconducting Cyclotron Laboratory (NSCL) in East Lansing, MI utilizes the coupled-cyclotron facility (CCF) and the A1900 spectrometer coupled to the S800 spectrometer for creating a particle flight path of about 58 m. The TOF detectors are placed at the A1900 extended focal plane and the focal plane of the S800. Particle rigidity is measured at the target position of the S800 [159,160]. A schematic of this setup, typical of setups utilizing the beamline for this sort of measurement, is shown in Fig. 3. For this particular setup, the rigidity measurement is done by running the experiment in dispersive mode, in which the maximum dispersion of the cocktail beam is at the S800 target position. A thin, position-sensitive detector is placed at this point. In order to minimize the uncertainties due to energy straggling in the detector, the position measurement is done with a detector that is as thin as possible and as close to the TOF stop as possible. In this case, micro-channel plate (MCP) detectors based on secondary electron emission were used [161,162].

As the NSCL upgrades to the Facility for Rare Isotope Beams (FRIB), production rates of more exotic nuclei should enable mass measurements of nuclei much farther from stability. It is predicted that nuclear masses for nuclei well past the second peak into the rare earth region will be possible [163].

The NSCL program has concentrated on a variety of mass measurements over the past several years [164], with a recent push toward neutron-rich nuclei of increasing mass [165]. Recently, masses of $^{59-64}$Cr were measured and compared to prior measurements. In addition, new masses of neutron-rich Ar, Sc, Mn, and Fe were measured, pushing the limits of mass measurements closer to the drip line for potentially early stages in the *r* process [165,166]. The purpose of these measurements was primarily to constrain nuclear reactions in the deep crusts of neutron stars. Thus, the nuclei measured are not yet on the *r*-process path, though they are useful for constraining systematics and mass models for neutron-rich nuclei. Prior measurements [167,168] using the same technique at the same facility have determined the masses of ^{61}V, ^{63}Cr, ^{66}Mn, and ^{74}Ni with resolutions of about 2×10^{-4}.

SPEG. The SPEG (Spectromètre à Perte d'Energie du Ganil) is a high-resolution spectrometer located at GANIL in Caen, France. The SPEG spectrometer consists of a 82 m flight path following an alpha spectrometer, so named for its beamline shape. The SPEG mass measurement program is established with a long history of mass measurements via the Bρ-TOF method [169–171].

The SPEG program uses microchannel plate detectors as the TOF start and stop signals. These have an intrinsic time resolution of ∼100 ps (FWHM). The setup also utilizes two rigidity measurements. Like the NSCL system, a rigidity measurement is made with the placement of an MCP at a dispersive focal plane. Another measurement is made after the TOF stop detector using two drift chambers.

Initial mass measurements were of light neutron-rich nuclei with accuracies down to a few 10^{-5} [172], and subsequent early measurements of neutron-rich nuclei from boron to phosphorus were conducted [173]. Additionally, the neutron-rich nuclei ^{29,30}Ne, ^{34,35}Mg, ^{36,37}Al, and $^{31-33}$Na were also measured [174], not only extending the region of known masses of neutron-rich nuclei, but also concluding that a region of known deformation includes ^{30}Ne. Subsequent measurements of masses in this region [175] have improved upon or extended the region of known masses of neutron-rich nuclei. In this case, the known mass region was extended to ^{47}Ar.

The SPEG collaboration has concentrated heavily on masses of neutron-rich nuclei near N = 16, 20, and 28. While this mass region is quite low with regard to the *r* process, the extension of light mass models in the neutron-rich part of the table of isotopes is important. Such a region may also be important for a "light element primary process" (LEPP). Members of the SPEG colaboration measured neutron-rich masses near the N = 20 shell closure, verifying a region of shape coexistence about N = 20 and N = 28 nuclei by measuring the masses of nuclei with $29 \leq A \leq 47$ [176]. These experiments were followed by an additional successful attempt to push the region of known nuclear masses of light nuclei closer to the neutron drip line [177,178]. Preliminary results of this model experiment presented first-time measurements of 7 new masses while the masses of 36 nuclei were significantly improved in the mass region A∼ 10–50. Recently, this region was further extended to include mass measurements of ^{19}B, ^{22}C, ^{29}F, ^{31}Ne, ^{34}Na, and other light nuclei [179] confirming the halo structure of several nuclei in this region. In this measurement, the B and C nuclei measured are presumed to be at the drip line.

Other facilities. The Radioactive Ion Beam Factory (RIBF) in Saitama, Japan has recently developed its SHARAQ spectrometer [180–182]. Coupling the spectrometer to the BigRIPS beamline, a 105 m flight path can be created. Time of flight detectors utilize diamond detectors [183], which are radiation hard and can sustain high rates. The high resolution of the SHARAQ detector allows for a fine measure of rigidity. Recent measurements of the masses of ^{55,56}Ca have resulted in mass resolutions of σ ∼150 keV and 234 keV respectively [184].

The collaboration between Beihang University and [185] the Heavy Ion Research Facility in Lanzhou (HIRFL) [186] is another promising activity, particularly as this collaboration has concentrated on detector development to improve the time resolution of TOF detectors. Recently, fast plastic scintillators with an intrinsic time resolution $\sigma \approx 5.1$ ps have been developed [187]. Preliminary tests at HIRFL with multi-wire proportional counters measure particle rigidity by position measurements in the dispersive focal plane. The intrinsic MWPC resolution is $\sigma \approx 1$ mm.

The Time-of-Flight Isochronous (TOFI) [188–190] is an early device to measure nuclear masses via time-of-flight. Designed for light-Z, neutron-rich nuclei, this device operates as a TOF spectrometer in an isochronous mode. In this mode, slower ions travel a shorter path. The TOF is then only dependent on A/Q of the given ion. This mode is employed in TOF measurements using rings as well (described in Section 3.1.4). As an earlier mass measurement system, the TOFI spectrometer has measured the masses of several neutron-rich isotopes between Li and P [188,190]. The resolution of these measurements was between about 200 keV and 900 keV.

3.1.4. Storage rings

Storage ring facilities function on a principle similar to the $B\rho$-TOF method. In this case, a beam of particles held at a specific rigidity travels in a closed-loop path in a ring. The frequency of the particle's path about the ring is used to determine the mass. The advantage of the storage ring is that it can operate with fairly low intensity beams to measure the TOF of the particle multiple times [191].

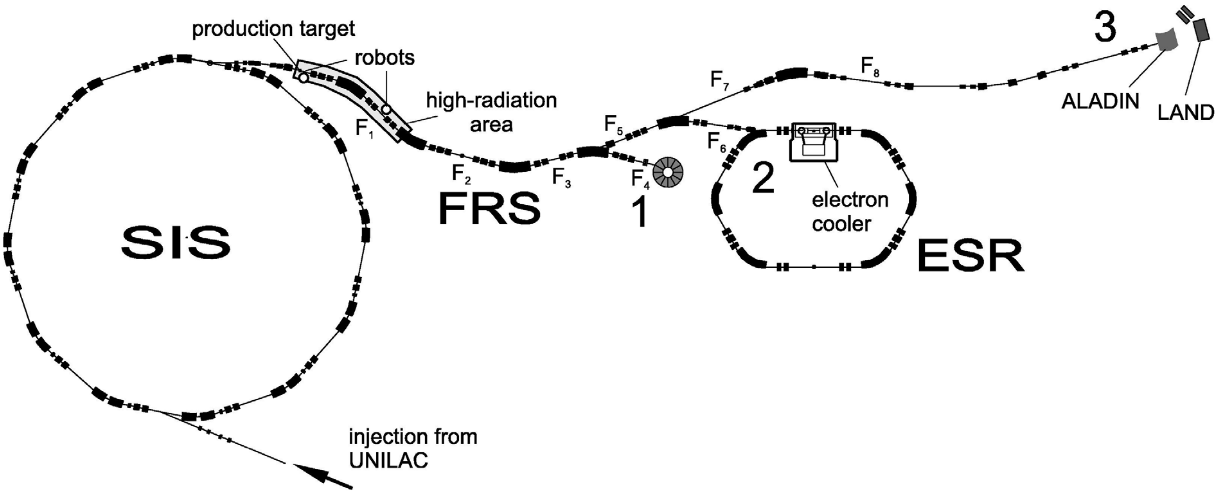

Fig. 4. A schematic setup of the GSI FRS-ESR ring, including downstream experimental areas [193]. (Used with permission.).

Storage rings are capable of measuring multiple masses in a closed-circuit ring. Particle frequency, f, about the ring of circumference C, is related to the mass-to-charge ratio [192]:

$$\frac{\Delta f}{f} = -\alpha_p \frac{\Delta(m/q)}{(m/q)} + \left(\frac{1}{\gamma^2} - \alpha_p\right)\gamma^2 \frac{\Delta\beta}{\beta} \tag{8}$$

where $\alpha_p = 1/\gamma_t^2$ is the so-called momentum compaction factor. High resolution is achieved via "cooling" in which the velocity spread approaches zero, $\Delta\beta \rightarrow 0$, or by operating the storage ring at the "transition point" in which $(\gamma^{-2} - \alpha_r) \rightarrow 0$. In either case, narrow variations in the frequency spectrum for a specific mass are measured.

Storage ring facilities are described below:

GSI-ESR. The storage ring located at GSI has been in operation since 1990. A figure of this experimental system is shown in Fig. 4 [193]. The heavy ion synchrotron SIS produces fragments which are analyzed in the fragment separator FRS and subsequently analyzed in the Experimental Storage Ring (ESR).

The ESR has a circumference of 108 m and a magnetic rigidity of 10 Tm. It is thus capable of storing uranium ions at 560 MeV/u. The rotational frequency of this ring (used in Eq. (8)) is upwards of 2×10^6 s^{-1}.

The ESR is capable of running in two modes. In Schottky mass spectrometry (SMS), measurements are made of particles nearly the same velocity, which is achieved via cooling the beam. That is $\Delta v/v \rightarrow 0$. Beams are cooled in the GSI-ESO by injecting a beam of co-moving electrons into the primary particle beam [194–197]. The electrons move transverse momentum from the beam by interacting with the beam, resulting in a beam in thermal equilibrium prior to removal of the electron beam. In isochronous mass spectrometry (IMS), measurements are made for particles with the same orbital period by selecting the central velocity of the beam to operate at the "transition point." That is, $\gamma \rightarrow \gamma_t$. In either case, the second term of Eq. (8) approaches zero, and the measurement accuracy can be improved greatly [198,199].

Recently, the FRS-ESR system has measured the masses of nuclei near the N = 82 waiting point $^{129-131}$Cd with an accuracy of 2×10^{-4} [200]. This measurement is useful for determining the shell gap at this point. On the neutron-rich side of stability, measurements were made using IMS for nuclei between Se and Ce by fragmenting a ^{238}U primary beam, extending the known mass landscape out by one more neutron [201]. These measurements could be useful in constraining mass models in this region. Approaching the r-process path in the rare earth region, masses of neutron-rich nuclei between Lu and Os were recently measured using SMS to similar accuracies [202]

HIRFL-CSR. The Heavy Ion Cooler-Storage-Ring (HIRFL-CSR) at Lanzhou [186] is part of the post-accelerator system at the Heavy Ion Research Facility in Lanzhou (HIRFL). Beams extracted from the cyclotron system are stored in the main ring (CSRm) and further extracted for radioactive ion beam experiments or storage in a separate experimental ring (CSRe). The main ring has a maximum design rigidity of $B\rho = 10.64$ Tm, and the experimental ring has a maximum design rigidity of $B\rho = 8.440$ Tm. These relatively high rigidities could enable good beam separation and identification for a variety of beam experiments. Studies of this device for mass measurement experiments have been performed [203].

This facility was able to measure the masses of the very neutron-rich $^{52-54}$Sc nuclei via the IMS method, finding a strong subshell closure for the N = 32 Sc isotopes [204].

The HIRFL-CSR was recently used to produce, identify, and study neutron-rich nuclei in the ^{18}O, ^{36}P, and ^{29}Mg region [205] by utilizing the Radioactive Ion Beam Line in Lanzhou (RIBLL2) to deliver beams to the CSRe [206]. This facility has also been used to examine the masses of proton-rich nuclei near ^{58}Ni [207].

RIKEN Rare RI-ring. The RIKEN Rare RI-ring facility at the RIBF was commissioned in 2015 [208]. It consists of a 60 m circumference ring with 0.5% momentum acceptance. At a beam energy of 200 A MeV, the revolution time is 355 ns. Unlike the GSI and HIRFL facilities, this ring is supplied by a cyclotron which feeds the BigRIPS. Particle identification is done within the BigRIPS rather than the ring. With this setup, it is possible to examine single particles in the ring. It is also worth noting that RIKEN currently has the highest intensity of ^{238}U beams in the world, making the rare RI-ring an attractive site for nuclear mass measurements. Current plans are to use the Rare-RI ring for mass measurements in IMS mode to achieve masses with a resolution on the order of 10^{-6}.

3.1.5. Other similar systems

Other systems include variants of TOF systems, including multi-reflection TOF systems and systems which can be described as hybrid techniques.

Two facilities employing similar techniques as TOF and cooling ring systems are described below.

MR-TOF. The MRTOF functions by injecting trapped ions into a drift tube with electrostatic mirrors on either end [209]. Reflecting the ion over multiple passages of the device increases the length of the flight path in a compact device. Ejection of the ions out of the end of the device into a timing detector provides a measurement of the flight time. Varying the number of times the ions can traverse the device will provide multiple measurements over various time ranges.

MRTOF systems have been installed at TRIUMF [210], ANL [211], GSI [212], ISOLDE [213], and KEK [214] among other places. The can be used as stand-alone devices or as auxiliary devices to purify beams prior to injection into another beamline or Penning trap, as in the case of the ISOLTRAP facility [213].

As an example, the TRIUMF TITAN facility recently probed the N=32 shell closure with the very neutron-rich Ti nuclei using its MR-TOF system with uncertainties of $\sim 3\times 10^{-7}$ [215]. In addition, the GSI facility was able to use its device to measure the mass of ^{213}Rn [216]. These two independent measurements convey the possible range of isotopic masses that might be measurable with MR-TOF systems.

MISTRAL. The ISOLDE MISTRAL spectrometer measures the nuclear charge to mass ratio by measuring the cyclotron frequency of ions in homogeneous magnetic fields [217]. Ion beams are focused onto an entrance slit in the field and extracted into an electron multiplier. At half-turns in the ion orbit, the ions pass through slits of an RF modulator, thus determining their kinetic energy and relating the RF frequency and the cyclotron frequency [218].

The MISTRAL experiment concentrates primarily on light, neutron-rich nuclei. Recent measurements have included ^{26}Ne, $^{26-30}$Na, and $^{29-33}$Mg [217,219]. Uncertainties of ∼20 keV are possible with this device. Other measurements have included halo studies of ^{11}Li and ^{11,12}Be [220,221].

3.2. β-decay rates and spectroscopy

Decay rates of the β-unstable nuclei along the r-process path are another fundamental property useful in understanding the r process. A knowledge of β-decay rates of r-process nuclei will provide a measure of the timescale of the r process as well as a knowledge of the nuclear structure of the involved nuclei. Along the r-process path, abundance distributions of r-process nuclei are related to the β-decay rates (compared to neutron-capture rates). Increased abundances are associated with slower decay rates.

As many β decays are to excited states of the daughter nuclei, coincidence measurements of γ-spectra are also useful in finding isomers. Isomeric states are useful in determining nuclear structure and decay characteristics of r-process nuclei [222].

3.2.1. RIKEN

Direct measurements of the half-lives of r-process nuclei are difficult as they generally require production of enough nuclei to obtain an accurate lifetime. A leader in this field is the RIBF at RIKEN which has pursued the measurement of β-decay half-lives using implantation-type methods [223,224]. The layout of the RIBF facility is shown in Fig. 5 [225].

AIDA. The most recent development of the β detection system is the Advanced Implantation Detector Array (AIDA) [226]. This detector system consists of a stack of double-sided silicon strip detectors (DSSDs) in which beams from the accelerator facility are implanted. Decays are measured by timestamping events from the implantation and subsequent decay. A system of newly-developed application-specific integrated circuits (ASICs) reduces the volume of electronics necessary to run this experiment. Because the experimental setup can be placed at the end of the beamline, it can operate parasitically while other experiments are running.

WAS3ABi. Similar to the AIDA device is the Wide Range Active Silicon-Strip Stopper Array for Beta and Ion detection (WAS3ABi) [227]. This device is similar in construction while used in conjunction with the EURICA spectrometer (described below).

Since their commissioning, the AIDA and WAS3ABi experiments have measured the β-decay half-lives of over 250 neutron-rich nuclei, with nearly 150 of these being first-time measurements [228–232]. These nuclei are close to, or on, the r-process path and cover r-process nuclei near the A≈130 peak, the A≈165 rare-earth hill, as well as neutron-rich nuclei from Kr to Tc with 90≤A≤149. In the case of nuclei near the A≈130 peak, the half-life systematics and shell effects

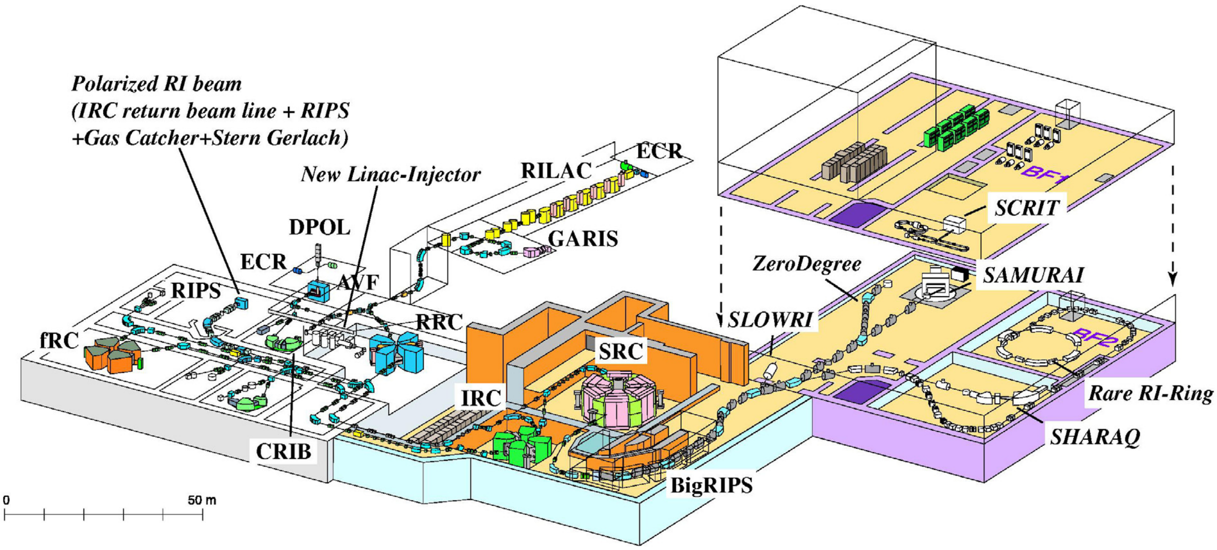

Fig. 5. Layout of the RIBF facility showing the coupled cyclotrons, SAMURAI spectrometer, and RI ring [225]. Used with permission.

were found to be robust, with no substantial changes in the gross nuclear structure as predicted by theory [230]. In the case of the Kr to Tc region, results indicate an enhancement in the rates in this region, resulting in a potential speed-up of the r process in this region. Studies of nuclei in the rare earth region, especially Nd, have been predicted to be important to the overall r process [98,99]. The newly measured half-lives will be useful for future theoretical evaluations of r-process sites.

EURICA. In addition to the half-life measurements at RIKEN, β-γ spectroscopy capabilities have also been added with the Euroball RIKEN Cluster Array (EURIKA) [233]. Launched in 2011, EURICA is designed to perform isomer and β-delayed γ spectroscopy. It consists of 12 segmented germanium detectors extracted from the RISING system at GSI [234]. This creates a nearly 4π germanium array which can be mounted around an active beam stopper system (such as WAS3ABi). The EURICA/WAS3ABi setup is mounted at the last focal point of the RIBF Zero-Degree Spectrometer. It has an energy resolution of 3 keV at $E_\gamma = 662$ keV and a photo-peak efficiency of 15% at $E_\gamma = 662$ keV. With EURICA, β-decay detection of implanted nuclei with coincident or delayed γ detection is useful for isomer searches, measurements of decay branching ratios, shape transitions and coexistence, low-lying yrast and non-yrast states, and single-particle levels.

The initial commissioning of EURICA examined decays of ^{16}C to ^{16}N to confirm the $0^- \rightarrow 2^-$ transition at 120.42 keV. The lifetime of this state was measured at 5.25 μs. The scientific program of EURICA began in 2012 to study isomeric states of ^{98}In, ^{95,96}Cd, and ^{94}Ag from the fragmentation of a ^{124}Xe primary beam. The EURICA array has been productive in its first year, with neutron-rich nuclei near the r-process path with $100 \lesssim A \lesssim 170$ [235]. Much of the EURICA experimentation has concentrated in this region of the isotopic chart.

The EURICA experimental configuration makes it quite useful for a variety of studies, particularly those with cocktail beams. Recent results from EURICA include verification and explorations of the N = 82 shell closure [47,49,236], multiple isomer searches of neutron-rich nuclei on or near the r-process path around the N = 82 shell [48,49,237–243], nuclear structure and deformation studies [244–246], studies of collective motion [247,248], and single-particle and particle-hole level studies [245,249].

3.2.2. CERN ISOLDE

Several studies of the β-decay rates have been performed with the ISOLDE Decay Station (IDS) [250]. This system is similar in setup and configuration to the AIDA/EURICA experiment at the RIBF in that it utilizes an implantation target surrounded by HPGE detectors. LaBr detectors can also be used for fast timing measurements of β-decay and γ coincidences.

Initial experiments of the IDS measured the ^{129}Sn levels from the decay of ^{129}In isomer decays [251]. Using this method, the lowest $1/2^+$ state of ^{129}Sn was measured with a lifetime of 19 ± 10 ps. This was followed by experiments to measure decay rates of neutron-rich $^{148-150}$Cs isotopes [252]. This provided experimental measurements of the half-life of these nuclei as well as a measurement of the decay scheme of ^{149}Ba.

While the IDS is a more recent implantation system, early experiments at the ISOLDE facility have used a moving tape collector to examine β- and γ-spectroscopic data for the N = 82 waiting-point nucleus ^{130}Cd [253]. An unexpectedly high energy of the 1+ level of ^{130}In was found. This level is populated primarily via the GT transition of ^{130}Cd. Spectroscopy of this nucleus also found a high Q value of 8.34 MeV for this decay, which agrees with earlier mass models that include shell quenching effects [38,254], though the agreement with more recent models including shell effects is not as good [255,256]. Additional measurements for the neutron-rich nuclei near the r-process path with an implantation tape include half-lives of ^{216}Bi [257], nuclear spectroscopy of ^{133}Sn [258], half-lives and spectroscopy of $^{130-132}$Cd [259,260], β-decay half-lives and β-delayed neutron emission, P_n, for the neutron-rich isotopes $^{94-99}$Kr and $^{142-147}$Xe [261], decay lifetimes and spectroscopy of ^{215,217,218}Bi [262–264], decay half-life and spectroscopy of ^{215}Pb [265].

3.2.3. ANL/CARIBU

The Argonne National Laboratory CARIBU facility has implemented a decay station to examine decay rates and spectra of fission fragments extracted from a ^{252}Cf source [266]. The two main components of the decay station are the X-Array and the SATURN device. The X-Array is an array of five HPGe clover detectors arranged in a box configuration for the measurements of primarily low-multiplicity γ-rays from implanted beams. SATURN is a moving tape system. The performance of this system was tested with ^{142,144,146}Cs β decays. In addition to decay data, γ, $\beta\gamma$, and $\beta\gamma\gamma$ coincidences were detected. With this device, the half-life of ^{144}Cs was measured to be 1.00(4) s. Recently, the decay scheme of ^{146}Ba up to energy levels of ∼2.5 MeV was also thoroughly measured with this device [267]. Another recent measurement with this system has been that ^{104}Nb β decay and subsequent γ transitions in the ^{104}Mo daughter [268]. Measurements of ^{160}Eu have recently been reported as well.

Also, a β-decay Paul trap, a radiofrequency quadrupole ion trap, has been developed at Argonne National laboratory [269]. This device provides the opportunity to surround a trapped ion cloud with a variety of detectors. Studies of the decay half-lives as well as kinematics of the electron and recoil nucleus provide a means to reconstruct the decay spectrum with high precision. Given the flexibility of this device, it is also possible to measure β-delayed neutron emission probability [270]. Recent decay measurements with the ANL Paul trap include ^{137}I. The recoil energy was measured in this proof-of-principle experiment.

3.2.4. NSCL

Decay measurements at the NSCL have implemented the NSCL Beta Counting System (BCS) [271]. Combined with the Neutron Emission Ratio Observer (NERO) [272] described in Section 3.3, decay half-lives as well as β-delayed neutron emission probabilities can be measured. The BCS is an implantation-type detector for fast beams. An upstream PPAC, PIN diodes, and a DSSD provide implantation position and lifetime measurements. This device has been used to measure the half-lives of several nuclei on or near the r-process path with $70 \leq A \leq 80$ and $90 \leq A \leq 110$ [273,274]. These include ^{90}Se, ^{105}Y, ^{106,107}Zr, $^{107-109}$Nb, and $^{108-111}$Mo. These half-lives can be compared to models to gauge the effects of shape changes, including the onset of triaxiality (in the case of the Nb isotopes). In the case of the neutron-rich Nb isotopes, the half-lives were similar to the FRLDM model, but lower than the FRDM model by roughly a factor of two. Results were similar for the Mo isotopes, with measured rates lower than the FRDM model by nearly a factor of three. Earlier results with the BCS include measurements of the half-life of the doubly-magic ^{78}Ni nucleus [275,276]. Combining this system with a γ-counting system in the same experiment has resulted in spectroscopy measurements of ^{120}Pd in an effort to understand proposed neutron shell quenching in the region below the A∼130 waiting point.

Further studies with the BCS have included lifetime measurements of the neutron-rich nuclei $^{77-79}$Cu, ^{79,81}Zn, and ^{82}Ga [277]. The rates found have been used in r-process models to reproduce the $78 \leq A \leq 80$ abundance pattern better than if rates from theoretical models were used. Half-lives for the neutron-rich $^{114-115}$Tc, $^{114-118}$Ru, $^{116-121}$Rn, and $^{119-124}$Pd near the proposed r-process path have also been observed with this method [278].

The NSCL BCS has also been used to study the decay of ^{90}Se [279]. The β-decay half-life of this nucleus has been studied to search for evidence of a subshell at N = 56, which would result in changes in the predicted r-process abundances, particularly as regards a possible weak r process. While this method found no subshell at N = 56, the method is readily applicable to other similar explorations. Comparisons of an r-process network calculation using these experimental results and half-lives determined using a QRPA calculation [280] have shown little difference in the final abundance distribution between the two.

3.2.5. GSI

The GSI silicon implantation beta absorber SIMBA detector array [281] is an implantation decay station similar to those mentioned above. It consists of two single-sided silicon strip detectors with strips oriented orthogonally and is used for x-y tracking. Two SSSDs were placed after these as front absorbers, followed by two double-sided silicon strip detectors used as implantation layers, and two additional rear absorbers. This device is used in conjunction with the GSI FRS and two MUSICs and TPC detectors which provide particle identification. This can also be used with the beta-delayed neutron (BELEN) system [282], which is a ^{3}He counter used for neutron detection to determine P_n.

Recently, the decay half-lives and P_n for several neutron-rich nuclei with A> 150 have been measured at the GSI-SIMBA facility [68,281]. This area is more difficult to reach experimentally because the production rates of the nuclei of interest are lower. In this work, the half-lives of $^{204-206}$Au, $^{208-211}$Hg, $^{211-216}$Tl, $^{215-218}$Pb, and $^{218-220}$Bi were measured, nine of which were measured for the first time. The values of P_n were also measured for ^{210,211}Hg and $^{211-216}$Tl. It was found that the values of P_n were comparable to or smaller than those predicted by global models.

The GSI experimental program has also incorporated an active stopper with the γ-ray detection array RISING [283,284]. With this setup, half lives for a broad range of nuclei near the doubly-magic ^{208}Pb nucleus have been measured in an effort to push decay measurements closer to the third r-process peak. These have been either first-time measurements or improvements on previous measurements. Nuclei that have been measured include $^{194-196}$Re, ^{199,200}Os, $^{199-202}$Ir, ^{203,204}Pt, $^{211-213}$Tl, and ^{219}Bi [285–291]. Further experiments with the same setup have examined the decay systematics of $^{211-213}$Tl, ^{215}Pb, and $^{215-219}$Bi including the γ-decay states of the daughter nuclei [292]. These experiments have been used to examine decay systematics in comparison to those extracted from the FRDM+QRPA mass model, which is commonly used r-process nucleosynthesis simulations. Also, a comparison with theoretical models can be used to gauge the importance of first-forbidden transitions in this region [290]. Near the N = 126 shell, shorter-than-expected half-lives can account for shifts in the third r-process peak as well as evidence of the significance of first-forbidden transitions in this region.

3.2.6. Jyväskylä

The JYFLTRAP system can also be used for the study of β-decay spectroscopy using the total absorption technique [293]. With this technique, direct measurements of the γ and β energies of the daughter products are made or deduced. Measurements of this type at the IGISOL facility [294] of the University of Jyväskylä were made by first purifying nuclei in the JYFLTRAP Penning trap [295,296]. After purification, nuclei are then implanted into a moving tape, similar to techniques mentioned previously. The tape then transports implanted nuclei to a Si detector system surrounded by a BaF_2 segmented γ spectrometer. On the neutron-rich side of stability, the decay energies, β spectra, subsequent γ energies, and branching ratios of ^{86}Br and ^{91}Rb have been determined [293]. While these nuclei are more relevant to reactor physics than the r process as they are not neutron-rich enough for the r process, the principle can be applied to r-process nuclei as well. Also, decay of r-process progenitors can proceed through these nuclei.

3.2.7. ORNL

Similar to the program at Jyväskylä, the Oak Ridge Holifield facility has performed studies of neutron-rich nuclei relevant to reactor physics. The Low Energy Radioactive Ion Beam Spectroscopy Station (LeRIBSS) [297] was equipped with a moving tape system along with two β detectors and four HPGE clover detectors for the study of nuclear decay spectroscopy. Early measurements of the r-process nuclei ^{82,83}Zn and ^{85}Ga were determined for the first time [298]. These results, combined with new models, have produced a significant change in the predicted abundances of the third r-process peak in a network calculation.

Although much of the work at the LeRIBSS facility has concentrated on neutron-rich nuclei near – but not on – the r-process path, other results are mentioned here as many of the nuclei measured may provide structure information for r-process post-processing. Using this facility, spectroscopy measurements have been made of ^{93}Br and ^{93,94}Kr [299]. The literature values of the decay rates and branching ratios were in good agreement with the measurements. This system was also used to examine the lighter, but very neutron-rich nucleus ^{85}Ge and its decay systematics [300], providing a partial level scheme of the daughter nucleus with several new transitions. For nuclei approaching the N = 82 closed shell, this system was used to measure the decay spectroscopy from decays of ^{124}Cd and ^{124,126}Ag [301,302]. The transport tape collector has also been used to study the decay spectroscopy of ^{137}I and ^{137}Xe [303].

3.2.8. Charge exchange

Weak interaction rates affect the r process through neutrino captures during deleptonization of the core [304] as well as the abundance distribution during post processing [46]. The former directly affects the electron fraction Y_e of the environment while the latter limits how quickly the r process moves to the high-mass region of the isotopic chart. For much of the r process, weak interaction rates are dominated by Gamow–Teller transitions. For this reason, significant understanding of the r process can be gained by understanding the GT-strength functions of r-process progenitor nuclei.

Charge exchange reactions, such as (p,n), (^{3}He,t) or (^{7}Be, ^{7}Li) reactions and their inverses have become very useful for mapping the GT-strength functions of many nuclei, providing a measure of the weak-interaction rates of many nuclei. The transitions brought about by these reactions mimic those produced in β decays, including transitions to excited states in daughter nuclei. In these reactions, the reaction cross section can be related to the strength function for β transitions [305,306].

An advantage of these types of reactions is that the heavy beams can be exotic beams at intermediate energies. Difficulties include the fact that these reactions are generally run in inverse kinematics to accommodate radioactive ion beams. As a result obtaining good resolution is difficult. Many charge exchange studies on neutron-rich nuclei have been limited to the lighter nuclei [307–309]. However, this technique has been developed and pursued at multiple facilities, and it remains an active field of study [310].

3.3. β-delayed neutron emission

Measurement of β-delayed neutron emission probabilities are useful for understanding the initial stages of the r process and the final stages during decay back to stability. This is important, as a loss of neutrons from progenitor nuclei tends to shift and smooth the final abundance distribution somewhat [311]. Thus, multiple experiments have been developed to measure the β-delayed neutron emission probability, P_n, for nuclei along the r-process path.

Early measurements of P_n concentrated on neutron-rich nuclei before the N = 82 shell closure and approaching the r-process path. This region is important not only because of prior studies of "shell quenching" in this region, but also because this is a region of production via fission of heavy r-process progenitors. The P_n values of ^{99,100g,101,102g,103}Y, $^{104g,104m,104m,105-110}$Nb, and $^{109-112}$Tc were measured [312] and compared to theoretical results. These measurements were implemented by a simultaneous β-decay rate measurement and a neutron detection measurement using ^{3}He counters embedded in a polyethylene moderator. In general, the P_n values measured were higher than those predicted with QRPA calculations using the FRDM [32] and ETFSI [37] mass models. The single exception was ^{110}Tc.

A significant amount of work to measure P_n has been conducted at the NSCL. Recent measurements of P_n have been performed on ^{104}Y and ^{109,110}Mo [273,313] with upper limits established for ^{105}Y, $^{103-107}$Zr, and ^{108,111}Mo. Half-lives have also been measured in these experiments simultaneously using the implantation technique described in the previous section. The values of P_n were measured with the NSCL Neutron Emission Ratio Observer (NERO) [314], an array of ^{3}He and BF_3 gas tubes arranged in a polyethylene moderator matrix. The combination of the NSCL BCS and NERO provides the capability to measure half-lives concurrently with neutron-emission probabilities. With this measurement, quadrupole deformation parameters could be determined for nuclei in this region. Triaxiality of nuclei in this region was also shown to contribute to the β-decay properties.

At GSI, the BELEN detection system [282] is used. This system is similar to NERO in that a polyethylene moderator is used to contain a detector matrix. The BELEN system differs in that it does not utilize BF_3 tubes. Recent measurements with BELEN have measured the P_n values of ^{210,211}Hg and $^{211-213}$Tl, targeting the region with $N \geq 126$. This measurement provided evidence that there is no particular model which can be globally applied to the entire r-process path that satisfactorily predicts β-decay half-lives and neutron branchings on both sides of the $N = 126$ shell closure.

3.4. Fission barriers and distributions

Fission cycling in the r process, particularly in sites with very large neutron-to-seed ratios (such as neutron star mergers), can be responsible for altering the final abundance pattern of the r process. If fissile nuclei are produced in the r process, the resultant nuclei are added to the progenitor distribution, altering the abundance distribution in the region of the r process coinciding with the fission products. Currently, measurements of fission fragment distributions and fission barriers are sparse for nuclei with masses above A$\sim$260. This creates uncertainties in r-process calculations.

Earlier measurements of fission yields of ^{235}U have investigated the yields of $^{124-132}$In [315] as well as $^{92-99}$Rb, $^{94-100}$Sr, $^{142-148}$Cs, and $^{143-149}$Ba [316]. These types of experiments are useful for establishing the systematics of fission fragment distributions. For example, studies of the In isotopic line have shown that the yields follow a Gaussian distribution, while those of the Rb, Sr, Cs, and Ba isotopes have shown that the distributions have a "wing effect" in which the decline of fragment yield with mass is less steep than that predicted by theory.

The IGISOL-JYFLTRAP facility has progressed in the study of the proton-induced and deuteron-induced fission of Th and ^{238}U [317–319]. In these studies, fission yields have been deduced by stopping fission products in the JYFLTRAP device. Fission products formed in a reaction chamber are separated in a dipole magnet before being cooled in an RFQ buncher and passed into the Penning trap. Isobaric chains of more than 20 different elements have been observed with this technique. The IGISOL facility is following up these measurements to develop the capability for measuring neutron-induced fission [320].

Recent techniques have also been employed at GANIL [321] and GSI [322,323] to study the fission of ^{238}U via transfer reactions with a ^{12}C target (at GANIL) or via Coulomb excitation (at GSI [324]). These experimental setups differ in the energy of the incident U beam, which is fully relativistic at GSI. Electromagnetically induced fission on ^{238}U is the equivalent of studying neutron-induced fission on ^{237}U with this technique. Fission fragments at GSI are identified using multiple sampling ionization chambers (MUSIC) with multi-wire proportional counters.

Elemental and mass distributions have been determined with a high degree of resolution and over a complete range of products. A good comparison to the GEF [325] code was found with some discrepancies related to the odd–even mass staggering as well as discrepancies in the symmetric valley.

Fission fragment mass distributions have been measured for nuclei as heavy as ^{256,258}Fm [73]. A shift in the systematics is noted for these two nuclei. While symmetric fission was observed for ^{256}Fm, a shift to symmetric fission was observed for ^{258}Fm. These systematics are useful for constraining fission models in this region.

3.5. β-delayed fission

The study of β-delayed fission is difficult experimentally as the branching ratios for this type of reaction are relatively low. The most recent studies have established experimental techniques using ^{178,180}Tl [326,327], ^{192,194,196}At [328,329], ^{200,202}Fr, and ^{186,188}Bi [330]. As fission experiments push to heavier, more exotic nuclei, the systematics of the fragment distribution as well as the fission rates can be better constrained. Recent progress in the development of higher-purity beams and detection techniques synchronized with beam characteristics is enabling fission studies of a larger variety of nuclei.

The β-delayed fissions of ^{180}Tl were studied at ISOLDE with a high-purity beam [331]. Asymmetric fission fragments from the ^{180}Hg daughter were observed. In this experiment, a rotating implantation target system was used. The Tl fragments were implanted into a target surrounded by Si detectors capable of detecting electrons, α-particles, and fission fragments. Germanium detectors were also used to detect photons in coincidence with the fission fragments. In addition to the fission fragment distribution, the most probable number of neutrons emitted in ^{180}Hg was found to be one. The ISOLDE group has also studied the β-delayed fission of ^{200,202}Fr, finding 112 fission fragments from ^{200}Fr and 6 from ^{202}Fr [330].

At GSI, the β-delayed fission probabilities and energies for ^{192,194}At were studied using the recoil-fission correlation technique [328]. Isotopes produced via fusion reactions were separated in the SHIP velocity filter [332] prior to implantation in a position-sensitive silicon detector array. The ensuing α and fission decays were then measured in this array. As with the previous experiment, germanium detectors were used to detect subsequent γ-decays. With this technique, the β-delayed fission of ^{192,194}At was identified, and an upper limit was placed on the total kinetic energy of the fission fragments. The β-delayed fission probabilities were then estimated based upon systematic arguments.

The same experimental technique at the SHIP facility at GSI has also been used to study β-delayed fission of ^{186,188}Bi, verifying fission with four events in ^{188}Bi and three events from ^{186}Bi. The probabilities of β-delayed fission in both cases were determined qualitatively to within a factor of five.

For the neutron-rich nuclei, recent measurements include ^{228,230}Ac [333,334]. After chemically separating ^{228}Ac from the decays of ^{228}Ra, and using mica fission track detectors and HPGe detector arrays, the β-delayed fission probability for ^{228}Ac was estimated at $(5 \pm 2)\times 10^{-12}$. A similar technique was used to extract ^{230}Ac from ^{230}Ra decays. The β-delayed fission probability of ^{230}Ac was tentatively found to be $(1.19 \pm 0.40)\times 10^{-8}$. Much earlier measurements of the half-lives of β-delayed fission of neutron-rich nuclei were made for ^{256m}Es [335], and ^{234gs,234m,236,238}Pa [336,337].

An excellent, recent compilation of known β-delayed fission precursors is found in Andreyev et al. [330].

3.6. Neutron capture rates

Neutron capture cross sections and rates control the speed of the r procees as well as the location of the r-process path (at least in cold scenarios). Also, the abundance pattern can be better understood by comparing the neutron capture rates and β-decay rates of the r-process progenitor nuclei [338,339]. Evaluated rates – both theoretical and experimental – are available on a number of databases, including the `REACLIB` [22] database and the `KADoNiS` [340–342] database.

As the effects of neutron capture rates are most affected at the closed shells, this part of the nuclear chart has seen a significant amount of study in the past several years. Direct, accurate measurements of (n, γ) cross-sections on r-process nuclei are currently challenging. However, these cross-sections can be determined indirectly via neutron pickup reactions such as (d,p) reactions in inverse kinematics [24,343,344]. In this case, the shell structure and the robustness of the $N = 82$ shell closure for the Sn nuclei have been determined.

It is also worthwhile to study neutron capture rates of stable nuclei or nuclei very close to stability. This is indirectly related to r-process nucleosynthesis as these sorts of studies provide a better understanding of the s process. The abundance distribution of r-process daughters can be determined by subtracting the s-process contribution from the observed distribution. (For a detailed review of the s process, see Käppeler et al. [345].)

3.6.1. Direct Measurements

Direct measurements of neutron capture cross sections on r-process progenitors are currently difficult as the required target is so short-lived. However, direct measurements of neutron capture cross-sections on stable targets or radioactive targets close to stability are possible. This is done at the CERN n\TOF facility. A recent measurement of the neutron capture cross section on ^{206}Pb was performed using the n\TOF neutron source [346]. While ^{206}Pb is predominantly an s-process isotope, a precise measurement of the neutron capture cross section can provide a means to subtract the s-process contribution from solar abundances, thus constraining the r-process contributions and calculations in the actinide region.

The n\TOF facility has also been used in a similar fashion to determine the r-process contribution of ^{209}Bi [347]. With a Maxwellian averaged cross section, the r-process contribution to ^{209}Bi was estimated to be 81 ± 3%.

3.6.2. Surrogate Reactions

Neutron capture cross sections are difficult to measure directly with r-process nuclei as both the target and beam are unstable. In the absence of direct measurements on unstable nuclei, surrogate reactions are possible [348–350]. These are reactions in which the same compound nucleus is formed as the desired reaction and its decay products are observed. In the case of a surrogate reaction, the direct and surrogate reactions for neutron capture would be:

$$\begin{aligned} &{}^{A}Z + n \rightarrow {}^{A+1}Z + \gamma \\ &{}^{A}Z + {}^{A'}Z' \rightarrow {}^{A'+A}(Z'+Z) \rightarrow {}^{A+1}Z + {}^{A'-1}Z' + \gamma \end{aligned} \tag{9}$$

In this way, neutron capture can be "simulated" and extracted from the surrogate reaction.

Because it has no excited states, the (d,pγ) reaction can be ideal as a surrogate for neutron capture. Deuterated targets (e.g., the plastic target CD_2) are available and can be used in this technique [351]. However, other techniques may also be used in which a neutron is left in the compound nucleus. For example, the (α,^{3}Heγ) has been studied as a surrogate for neutron capture.

The surrogate technique has been studied by the Rutgers/ORNL group [349,352,353], LLNL [350,354], and CNRS [355].

3.6.3. Coulomb Dissociation

Coulomb dissociation can also be used to determine neutron capture cross sections. With this technique, a radioactive ion beam incident on a target is excited above the neutron emission threshold. This technique requires a neutron detection system. The LAND setup at GSI employs this method. Recently, Coulomb dissociation of ^{18}C has been used to determine the thermally averaged neutron capture cross section $\sigma_{n\gamma}$ on ^{17}C [356]. These results were used to determine that the ^{17}C(n, γ) reaction has no pronounced influence on the second and third peaks of the *r* process in neutrino-driven wind models and in neutron star mergers.

3.6.4. β-Oslo Technique

A newer, novel technique [357] is based on the existing Oslo method [358,359]. This technique, known as the "β-Oslo" method, measures the simultaneous β decay of an implanted isotope in coincidence with the sum energy of all emitted photons in the daughter nucleus. The neutron level densities and γ strength functions can then be extracted simultaneously and used as inputs for (n,γ) cross section calculations with excellent results.

The β-Oslo has the advantage of working with very low beam rates of ~ 1 s^{-1}. It has been used recently to extract neutron capture rates on ^{75}Ge [357] and ^{70}Ni [360] at the NSCL.

3.6.5. Other facilities and techniques

Using the photoactivation technique, a beam of photons is used to excited a target above the neutron threshold. As an example, branch point nuclei in the *s*-process path nuclei can be studied. These are then used to accurately separate contributions to nuclear abundance distributions from neutron-capture processes. One particularly interesting experiment was the study of the ^{187}Re(γ,n) reaction to determine the ^{186}Re neutron capture cross section [361]. While this nucleus is not an *r*-process progenitor, its capture cross section is important in understanding the *s*-process contribution to the *r*-process cosmochronometer ^{187}Re.

The activation technique has been used to study the (n, γ) cross section of the long-lived isotope ^{182}Hf [362]. Because of its long half-life, this nucleus can be used as a target which was illuminated with neutrons at $kT = 25$ keV. With this technique, the Maxwellian averaged cross sections have been found.

A particularly interesting proposal for the measurement of neutron capture reactions in inverse kinematics involves the use of a storage ring with a neutron target [363]. The storage ring, such as the GSI ESR [193] would be capable of storing an intense beam of short-lived nuclei. The neutron target could be implemented by passing the beamline of the storage ring through a reactor core. With this method, assuming a neutron flux, $\phi = 10^{14}$ cm^{-2}s^{-2} and a stored particle intensity of 10^{13} s^{-1}, a daily reaction rate of $20\times\sigma$ per day could be measured, where σ is the estimated neutron capture cross section in mb. Thus, in a single day, cross sections on the order of mb could feasibly be measured. The neutron-induced reaction would be detected via the change in the velocity of the beam particles.

3.7. Nuclear structure studies

Far from stability, in addition to nuclear masses and decay half-lives, much can be known about the *r*-process path through a variety of nuclear structure measurements. Nuclear structure knowledge can provide additional information for theoretical predictions of masses, halflives, and neutron capture rates. Shifting and appearance of neutron major and minor shells near the *r*-process path can result in a shift in predicted neutron separation energies, and hence, the location of the path itself. Shape transitions are closely related to this, as deformations may result in a modification of the presumed shell structure.

3.7.1. Neutron separation energies and shell closures

The study of shell closures, particularly the N=82 closure, has an extraordinarily long history, with a variety of experimental and theoretical procedures used to explore this interesting region of the *r*-process path [49,230,246,253, 260,364–375]. Shell structure can be manifested in a variety of experimental observables, including half-lives [365,372], β-spectroscopy [366,370], energy levels and transition probabilities [367,369,373–375], and mass measurements [371].

In-flight fission has made it possible to push the limits of neutron-rich nuclei for the purposes of exploring structure far from stability. For example, the WASABi detector (mentioned in Section 3.2.1) was used to determine the γ energy spectrum of ^{126}Pd and ^{128}Pd produced via in-flight fission of ^{283}U [47]. Photons were detected from nuclei implanted in the WASABi endstation. Intensities of the Pd γ-decays were then used to assign spins to nuclear levels. As with the (d,p) reactions mentioned above, the robustness of the N $= 82$ shell closure was confirmed in the Pd isotopic chain.

3.7.2. Isomers

Isomeric states are worth studying as they can provide information on nuclear structure, including single-particle states and β-decay rates.

Isomeric states from *r*-process nuclei may be rare or short-lived [e.g. 376], which would make them indistinguishable from β-delayed γ-signatures in examining the light output signature of an *r*-process site. While atomic absorption lines are generally able to distinguish individual elements, isomeric transitions can be used to identify isotopes in a potential *r*-process site. Astronomical γ-ray observations (described in Section 5.3.1) present the possibility for isotopic identification of the *r* process occurring in real time [377]. Observing short-lived isomers would require either prompt gamma observations of an *r*-process site or observations of photons from long-lived β decays which would occur during the late stages of decay of nuclei back to stability.

In many cases, isomers can be found in conjunction with other measurements. For example, the TITAN Penning-trap mass spectrometer has found a low-lying 80 keV isomer of the neutron-rich nucleus ^{98}Rb while measuring the masses of the Rb and Sr isotopes in the $A \approx 100$ mass region [152]. The EURICA experiment has also been equipped with former EUROBALL HPGe detectors and has been used to find isomers in the neutron-rich nuclei ^{126,128}Pd nuclei, providing further evidence of a robust N = 82 shell closure [47].

Former EUROBALL detectors have also been used to find high-spin states of the neutron-rich ^{204}Pt nucleus at the N = 126 closed shell. This implantation-type experiment has identified a 55 μs high-spin isomer with $J^{\pi} = 7^{-}$ [64]. While this may be short-lived for observational purposes, the versatility of implantation experiments and simultaneous isomeric searches is evident with this setup.

3.8. Current and future facilities

With the advent of new radioactive ion (RI) beam facilities worldwide, the possibility of directly probing the *r*-process path is becoming a reality. Some facilities are already operating, while others are under construction [378]. The following is a representative list of major RI beam facilities with user programs.

3.8.1. ATLAS

The ATLAS (Argonne Tandem Linac Accelerator System) facility [379] at Argonne National Laboratory has made major contributions to a variety of astrophysics experiments over the years. Perhaps the most notable recent contribution by the ATLAS facility has been the development of the Californium Rare Isotope Beam Upgrade (CARIBU).

With CARIBU, heavy, neutron-rich beams are produced by extracting fission fragments from a 1 Ci ^{252}Cf source, stopping them in a gas catcher, separated, and re-accelerated [380]. Neutron rich beams in the region roughly between Zn and Dy between stability and the *r*-process path can be produced with this facility.

3.8.2. FRIB

The Facility for Rare Isotope Beams (FRIB), located at the site of the NSCL in Michigan, USA, is currently undergoing construction with a target completion date of 2020. It consists of a superconducting linear accelerator capable of primary beam energies of up to 200 MeV/A for uranium. This facility will be coupled to a reaccelator for studies with low-energy (<12 MeV/nucleon) secondary beams. The low-energy facility currently exists and is being used coupled to the existing facility.

3.8.3. GANIL/SPIRAL2

GANIL recently upgraded to the SPIRAL2 facility consisting of a superconducting linear accelerator and fragment separator [381]. It is capable of providing beams through a variety of mechanisms, including neutron-induced, fisison, in-flight production, and isotope separation online. The facility is complemented with a large range of detection systems. SPIRAL2 has an associated high resolution spectrometer with a mass resolving power $\Delta m/m \approx 1/31000$ [382]. Work at SPIRAL2 can concentrate on superheavy element searches, intense beams of fission products, and high-resolution spectroscopy.

3.8.4. GSI-FAIR

When complete, the Facility for Antiproton and Ion Research (FAIR) [383] at GSI will be one of the largest research projects worldwide. Full operations are planned for 2025 following a planned commission in 2022. This facility will accommodate several experimental programs including QCD studies, decay spectroscopy, production of exotic nuclei, isomeric studies, trap experiments, and a host of other experimental programs relevant to nuclear astrophysics.

The FAIR facility is expected to provide uranium beams with an intensity of up to 10^{12} ions/s with a high energy of 1.5 GeV/A. Intense secondary beams can be produced from this.

3.8.5. HIRFL-RIBBL/RIBBL2

The Radioactive Beam Line in Lanzhou (RIBLL) [384] began operation at the Heavy Ion Research Facility of Lanzhou (HIRFL) since 1998. A subsequent upgrade to RIBBL2 [385]. This beamline is coupled to the synchrotron cooler storage main ring (CSRm) and the experimental storage ring (CSRe) in the HIRFL-CSR sytem. RIBBL2 is used to deliver isotopes to the CSRe for mass measurement experiments [206].

3.8.6. ISOLDE/HIE-ISOLDE

The HIE-ISOLDE [386], an upgrade to the original ISOLDE facility [387], provided its first radioactive beams with energies up to 5.5 MeV/A in 2016 and 10 MeV/A in 2018. An intense, high energy proton beam (1.4 GeV, 2 μA) is produced in the Proton Synchrotron Booster of CERN. Low-energy radioactive beams are then produced in thick targets by spallation, fragmentation, and fission reactions between the proton beam and the target. Beams are then post-accelerated in the REX linac. The Higher Intensity and Energy (HIE) upgrade provides an increase in intensity and energy. A variety of structure experiments of astrophysical interest have been performed since the recent upgrade, including studies near the ^{132}Sn region of the isotopic chart.

3.8.7. RIBF

The Radioactive Ion Beam Factory (RIBF) in Saitama, Japan is an in-flight RI beam separator [388]. It is a coupled cyclotron facility capable of producing heavy primary beams with energies up to 350 MeV/A. Exotic beams are produced via fragmentation and separated in the BigRIPS fragment separator. The facility also has the capability of producing fission products via in-flight fission.

3.8.8. RAON

The RAON facility in Korea is currently under construction. It will contain a variety of instruments, including KOBRA (KOrea Broad acceptance Recoil spectrometer and Apparatus), LAMPS (Large Acceptance Multi-Purpose Spectrometer), and ZDS (Zero Degree Spectrometer) [389]. Each of these devices can be used for a variety of experiments with ranges of acceptance, resolution, and energy. This facility is predicted to be capable of primary beams of 600 MeV protons at 600 μA and 200 MeV/A uranium beams at 8.3 μA.

3.8.9. TRIUMF/ARIEL

The latest upgrade to the TRIUMF facility the Advanced Rare Isotope Laboratory (ARIEL) [390], is a versatile facility targeting fundamental nuclear physics, medicine, and materials science. It contains a 500 kW, 50 MeV electron accelerator (e-linac), which produces rare isotopes via photo-production and photo-fission. A secondary proton beam from the 500 MeV cyclotron can also be used to produce rare isotopes via spallation, fragmentation, and fission.

Actinide targets in the e-linac will result in very intense neutron-rich beams while avoiding contamination that are typically produced via proton-induced spallation and fragmentation. This facility was successfully commissioned in 2014.

4. Candidate astrophysical environments

The unambiguous identification of a single dominant site for *r*-process nucleosynthesis (if there is one) has remained elusive. Often the field has been convinced of its certain identification only to be later disappointed. The widespread hopes, after the observation of a universal characteristic pattern of elemental abundances for elements heavier than iron have not yet been fulfilled. There is currently a wellspring of support for binary neutron star mergers as the primary site for the *r* process based upon a number the observations such as the GRB170817 kilonova [14,391–397] associated with gravitational waves from GW170817, and the apparent rare event deduced to have occurred in the Reticulum-*II* dwarf galaxy [398–400].

The *r* process is best characterized as a sequence of rapid neutron captures. It requires both an explosive environment and neutron-rich matter at high densities.

There are a number of astrophysical environments that can achieve this. These include: shock ejected material from core collapse supernovae, neutrino-driven winds in supernovae, shock-induced explosive helium burning in supernovae, magnetic-turbulence driven ejecta in magneto-hydrodynamic jets from supernovae and collapsars, accretion disks of neutron stars or black holes, tidal or neutrino driven ejection from the mergers of two neutron stars or a neutron-star plus black-hole binary, or even neutron-rich regions in inhomogeneous big-bang models.

Over the past half century some of these models have been ruled out as the physics of the environments have been better elucidated. On the other hand, core-collapse supernovae and neutron star mergers (NSMS) have remained the two most favored candidates. Many researchers are now even convinced that NSMs are the dominant site for the *r* process [401]. Observations [402] showing the arrival of heavy-element *r*-process abundances in very low-metallicity stars would favor the short stellar lifetime of core-collapse supernovae (CCSNe) as the *r*-process site. However, identifying the occurrence of an *r*-process environment and its location within models of CCSNe has been difficult [403,404].

We now summarize the basic astrophysical considerations common to all such models. Thereafter we devote a section to the observational constraints in more detail. Thus, the section that follows will take up the above model list, and deepen the discussion of each of the candidate models.

4.1. The basics

The *r* process involves a sequence of rapid neutron captures in an explosive environment [1,405]. Although many sites have been proposed for the *r* process, whatever the environment, it can be shown that the Solar-System *r*-process abundances are for the most part well explained by simple β-decay flow in a system that is in approximate $(n,\gamma) \leftrightarrows (\gamma,n)$ equilibrium.

Under these conditions, the relative abundances of isotopes of a given element are simply determined by the equations of nuclear statistical equilibrium (NSE).

$$\frac{n(Z,A)}{n(Z,A+1)} = \frac{1}{n_n}\left(\frac{2\pi\mu kT}{h^2}\right)^{3/2} \times \frac{G_A G_n}{G_{A+1}} e^{-Q_n/kT} \quad , \tag{10}$$

where μ is the reduced mass of the neutron plus isotope ^AZ, h is Planck's constant, k is the Boltzmann constant, and T is the temperature. The quantity G_A is the partition function for nucleus, ^AZ, Q_n is the neutron capture Q value for isotope ^AZ (or equivalently the neutron separation energy for the nucleus ^{A+1}Z), and $n(Z,A)$ represents the number density of an isotope ${}^{A}Z$. Note, however, that this formula neglects a small correction [406] for the difference between Maxwellian and Planckian distribution functions for the photons.

Eq. (10) defines a sharp peak in abundances for one (or a few) isotopes within an isotopic chain. The flow of β decays along these peak isotopes is then known as the r-process path.

The location of the r-process path peak is roughly identified [1] by the condition that neutron capture ceases to be efficient once $n(Z, A+1)/n(ZA) \lesssim 1$. Taking the logarithm of Eq. (10) and inserting the numerical terms, the r-process path can be identified by the following relation

$$\left(\frac{Q_n}{kT}\right)_{\rm path} = 2.30\left(35.68 + \frac{3}{2}\log\left(\frac{kT}{\rm MeV}\right) - \log\left(\frac{n_n}{\rm cm^{-3}}\right)\right) \ . \quad (11)$$

The elemental abundances $n(Z, A)$ along this path are then determined by the flow of β decays,

$$\frac{dn(Z,A)}{dt} = \lambda_{Z-1} n(Z, A-1) - \lambda_Z n(Z, A) \ , \quad (12)$$

where the total β-decay rate of each element along the path is given by the weighted sum of β-decay rates for each isotope $\lambda_\beta(Z, A) = 1/\tau_\beta(Z, A)$:

$$\lambda_Z = \sum_A n(Z, A)\lambda_\beta(Z, A) \ . \quad (13)$$

For a typical r-process temperature of $T_9 \sim 1$, the requirement that the r-process path reproduce the observed abundance peaks at $A = 80,\ 130$ and 195, implies that the r-process path halts at waiting points in the beta flow near the neutron closed-shell nuclei ^{80}Zn, ^{130}Cd and ^{195}Tm. For a neutron density sufficiently high ($n_n \gtrsim 10^{20}$ cm^{-3}) so that the neutron capture rates exceed the β-decay rates for these isotopes, the peak abundances along the r-process path must be for isotopes with $Q_n \sim 1$–3 MeV, and thus $(Q_n/kT)_{path} \sim 10$–30.

This constraint on Q_n, however, concerns the conditions near *freeze-out*, when the final neutrons are exhausted at the end of the r process. At this point, the system falls out of NSE and nuclei along the r-process path decay back to the line of stable isotopes.

Earlier in the r process the neutron densities can be quite high and the r-process path is shifted to more neutron-rich nuclei. For example, in the neutrino driven wind (NDW) models of [12], the r-process conditions begin with a neutron density of $n_n \approx 10^{27}$ cm^{-3} and a temperature of $T_9 \sim 2$. The density is also much higher ($> 10^{32}$ cm^{-3}) when the material is first ejected from the proto-neutron star. Such conditions can also be achieved for an r process which occurs during NSMs [74,407–412].

Of course, as the r process freezes out, one must make a detailed accounting of the full r-process reaction network, i.e.

$$\begin{aligned}\frac{dn(Z,A)}{dt} &= n(Z, A-1)\phi_n\sigma_{n,\gamma}(Z, A-1)\\ &+ n(Z, A+1)\phi_\gamma\sigma_{\gamma,n}(Z, A+1)\\ &+ n(Z-1, A)\lambda_\beta(Z-1, A)\\ &+ \text{terms with } (n,p), (n,\alpha), (p,\gamma), (\alpha,\gamma),\\ &+ (n, \text{fission}), (\beta, n), (\beta, \text{fission}), \quad \text{etc.}\\ &- n(Z, A)[\phi_n\sigma_{n,\gamma}(Z, A) + \lambda_\beta(Z, A)\\ &+ \phi_\gamma\sigma_{\gamma,n}(Z, A) + \cdots]\end{aligned} \quad (14)$$

where ϕ_n and ϕ_γ are the time-dependent neutron and photon fluxes, respectively.

A number of network codes exist in the literature. For more details about the implementation of such codes see, for example, Meyer [413].

5. Astronomical observations

5.1. Messengers of the r process

Cosmic nucleosynthesis processes including the r process are recognized from their characteristic abundance patterns of atomic nuclei: Nuclear reactions rearrange the nucleons of the original composition of nuclei in ways that characterize the nuclear burning conditions, i.e. the *process* and *site* of nucleosynthesis. Therefore, the ideal messenger of the r process would be the observation of the abundance pattern of isotopes from an r-process event.

However, such nucleosynthesis events are typically launched from a hot and dense environment, which is optically thick to all types of radiation, including characteristic nuclear or atomic lines. Only the explosive dilution makes us register messengers from the origin of the nucleosynthesis process. Neutrinos may escape from dense nucleosynthesis sites, and have been direct messengers for nucleosynthesis in our Sun [414] and for SN1987A [415]. Next to this, γ rays from the radioactive decay of short-lives isotopes created in the nucleosynthesis event may provide a rather direct, isotopic, and characteristic messenger [416]. These have only been measured for few supernova explosions and their remnants, e.g., SN1987A [417], Cas A [418–420]. Recently isotopes of iron-peak nuclei have been measured for the first time for a supernova of type Ia with SN2014J [94,95].

Being a neutron capture process, the characteristic signatures for the *r* process are expected to show up in the nuclei well beyond the iron peak. The abundance of such heavy isotopes is generally low compared to lighter elements of the iron peak or below. Additionally, the short radioactive decay times of neutron-rich heavy isotopes disfavor the direct observation of their decay, due to a substantial envelope absorbing radiation from the inner nucleosynthesis products of the core-collapse supernova of a massive star. For supernovae of type Ia with less of an overlying envelope, conditions for an efficient *r* process are not generated, and the predominant ejecta composition peaks at around iron nuclei based upon the conditions of nuclear statistical equilibrium (NSE) realized in the SN Ia environment.

Merging neutron stars, however, could provide more favorable conditions for the direct observation of nuclear decays, as neutron-capture nucleosynthesis may occur near the surface of the event. This material is only occulted by matter liberated from the merging compact stars in the event itself. Nevertheless, limitations of instrumental sensitivities require nearby *r*-process events for such direct messengers ($\leq$3 Mpc), and have not been successfully recorded.

Next to this, the electromagnetic evolution of a nucleosynthesis event provides information about the event and its nucleosynthesis processes, as the radioactive energy of newly created isotopes is absorbed in an envelope, and converted through scattering and absorption processes into radiation at lower energy, where observing capabilities are well developed. This is abundantly exploited in the case of supernovae, and has recently also been realized for the case of an *r*-process event through observation of GW170817 in a broad range of electromagnetic radiation, following the trigger from a characteristic combination of gravitational-wave and γ-ray burst signatures [14].

For supernovae, the light emission can be traced from the photospheric phases to the nebular phases. That is, optically-thin phases of the supernova spectra can be observed for months after the event to obtain a kind of tomography [421]. For *r*-process events, both the amount of the envelope and radioactive material may be smaller, and typical radioactivity may be more short-lived. Hence, the observing window is much shorter, consisting of measurements for a few days only. Nevertheless, the GW170817 kilonova has provided us with a unique opportunity, which is reminiscent of the way in which observations of SN1987A brought insight into the astrophysics of core-collapse supernovae.

The main body of astronomical observations that have established the study of *r*-process nucleosynthesis is based upon atomic-line spectroscopy of starlight from metal-poor stars which are enhanced in their heavy-element abundances. Since Fraunhofer's discovery of characteristic absorption lines in the solar spectrum, the astronomical window between about 350 and 700 nm has served as the main tool for cosmic elemental abundances. With a spectral resolution of $\lambda/\delta\lambda \gtrsim$50,000, atomic lines can be discriminated for their detailed analysis. We note that these are elemental rather than isotopic abundances. Isotopic line offsets are mostly smaller than the line widths that result from thermal and turbulent motions (few km s^{-1}) in these stellar atmospheres. From optical to infrared spectroscopy, rarely is spectral resolution sufficient to disentangle isotopic signatures of absorption lines from heavy element species. However, isotopic ratios of an element (e.g. Eu) can be estimated from the profile details of photospheric spectral lines. This is because the hyperfine splitting from the total nuclear mass and nuclear spin is sufficiently large so as to shift the line position enough that the line shape distortion can be measured [e.g. 5,92].

The integrated area of an absorption line then provides a measurement of the abundance of the absorbing atomic (or molecular) species in the photosphere of the star. Such absorption lines from heavy elements have been measured in metal-poor stars (i.e. where the abundance of iron was much lower than in typically-observed stars). In particular, there is a small subset of these stars ($\sim$few percent) which show substantial enhancements in heavy-element signatures. Stars of low mass (one $M_\odot$ and below) evolve rather slowly. Their evolution time is comparable to or exceeds the age of the universe. Their structure changes very slowly if at all, and their present day photospheric composition for the most part still reflects the gas from which they were formed. If the photosphere then shows a low content in heavy elements in general, as most-easily traced through absorption lines of neutral and ionized iron, then we call such stars *metal-poor*. The iron abundance in stellar-photosphere data has been found to have a dynamic range of eight orders of magnitude, and the currently-observed record lowest iron abundance is $10^{-7.8}$ times that of our Sun [422].

We call it *Galactic archeology*, when stars across a range of metallicities are analyzed for their signatures from nucleosynthesis before their original formation: The material from which such a star has been formed is the object that is observed. A difficulty in the spectroscopic measurement of neutron-capture elements, however, is the weakness of the spectral lines of these elements and the severe contamination due to features of other elements (e.g., Fe, Ti, molecules). This difficulty is reduced in the analysis of metal-poor objects having an excess of elements attributed to the *r* process such as Eu. As a result, many spectral lines of neutron-capture elements that are not measured even for the solar spectrum are used in the analysis of Eu-enhanced metal-poor stars.

These observations have then shown that the relative abundances among heavy elements, that is, the abundance pattern, appears to be very similar to the *r*-process abundance pattern observed for our Sun, after the *s*-process contributions to solar abundances have been subtracted. This pattern remains the same, even though metallicity (as traced through the iron abundance from its well-measured absorption lines) changes over orders of magnitude. This is a strong indication of universality of the underlying nucleosynthesis [423], and has been the main stimulus for searching the origins of this universal *r*-process nucleosynthesis. We discuss these results in more detail in Section 5.4.

The elemental abundance pattern of the *r* process characteristically shows several peaks, related to the neutron magic numbers piling up abundances along the reaction path of neutron captures and β decays that characterize the *r* process: $N = 50$ leads to a peak in the element range $Z \sim 35$ with elemental masses around 80, i.e. ^{80}Se, characteristic elements being Sr, Y, and Zr that can be measured in stellar photospheres. $N = 82$ leads to a peak in the element range $Z \sim 54$ with elemental masses around 130, i.e., ^{130}Te, characteristic elements being Xe, Te, and I; as these are difficult to observe in stellar spectra, Ba and La lines and their abundances are often taken to characterize this second *r*-process peak.

There is an intermediate, minor, abundance peak in the elemental mass range of mass numbers 150–170, the rare elements, characterized by La and the lanthanides. The magic number at $N = 128$ leads to a peak in the element range $Z \sim 78$ with elemental masses around 195. This is the third *r*-process peak at ^{195}Pt. Characteristic elements near this peak that can be observed through spectral lines are Os and Ir. Beyond the third peak, the actinides U and Th have also been measured in stellar photospheres. The entire range of elemental abundances between Ba and Eu ($Z = 56$–68) was considered to be characteristically different from the abundance pattern of elements as expected from the *s*-process. Hence this range is also often used as indicative of the *r* process. In terms of easy observational access, Eu has a prominent role, with its two main stable isotopes ^{151}Eu and ^{153}Eu. Both are unshielded by other stable nuclei against β decay from the *r*-process path.

The difference with respect to nucleosynthesis from the *s*-process is an observational necessity to analyze nucleosynthesis contributions from the *r* process. Therefore, it may sometimes be difficult to draw significant conclusions on the *r* process. For example, Pb abundances are considered to be 80% due to the *s*-process. In general, however, roughly equal portions of the elements heavier than iron are considered to originate from either the *s*- or *r* process. Hence, for many elements the abundance pattern of the *r* process is a significant constraint.

Photospheric abundances inferred from absorption line spectroscopy are subject to some systematic uncertainty. This is the necessity to model the thermodynamic conditions under which the atomic lines are excited. In order to reduce such systematics, one often resorts to similar types of stars. That is, one considers similar spectroscopic types of stars, among which such systematics should be small. Also, selecting field stars is helpful. The hope is to find a typical gas composition to the star that is being observed. In the extreme case, *solar twins* have been used for precision spectroscopic abundance determinations, reaching a level of 0.01 dex [424]. However this is done at the cost of a small sample size.

The formation environment of stars might vary, as they could either be forming from well-mixed, or from less representative interstellar gas. The latter case would then not trace the earlier nucleosynthesis history and be biased, either from a nearby group of young stars and their ejecta, or from a nearby supernova event, or from a companion star transferring mass. This is in particular evident in stars in the Galactic halo, in which the impact of an individual event is more significant due to the overall-low metallicity, and presumably slower compositional evolution of the halo gas.

In the disk and bulge, stellar activity and feedback is large. Thus, a mixture of sources and processes may contribute to a diverse imprint on the gas composition out of which the next-generation stars have been formed. These are still alive today so that their photospheres provide a messenger of the *r* process. Recently, observations from ^{26}Al radioactivity (decay time $\tau \sim$ My) in the Galaxy have indicated that massive-star and supernova debris preferentially are ejected into large superbubbles, as these stars are formed in clusters [425]. It may thus take tens of My or more for such ejecta to cool and be recycled into the next-generation stars. It is unclear how efficient the ejecta from rare and non-clustered nucleosynthesis sites may mix and merge into star-forming material.

5.2. The solar abundance reference

Fig. 6 shows an example of the isotopic abundance distribution of solar-system *r*-process material obtained [426] after subtraction of the *s*-process contribution. Newer versions of this decomposition can be found in the literature [e.g. 402]. This distribution is, perhaps, the most important reference with which to compare the predictions of *r*-process models [e.g. 427,428].

Heavy elements with mass number (A) larger than $\sim$70 originate from neutron-capture reaction sequences from both the *s*- and *r* processes. The contributions of the two processes are apparent from the double abundance peaks corresponding to the neutron magic numbers (50, 82, and 126). These appear at slightly different mass numbers due to the different reaction paths: The *r* process reaches magic number nuclei during a neutron irradiation burst. Thereafter, β decays shift the abundance peaks toward lower mass numbers, while the *s*-process path directly produces abundance peaks at magic-number nuclei.

Since the *s*-process yields are basically determined by reactions along the region of stable nuclei, modeling of the *s* process is less uncertain and better established than that of the *r* process. Because the nuclear properties of neutron capture and binding are the drivers of the *s*-process, and irradiating nuclei with neutrons at such a low fluence leaves sufficient time for intermediate β decays; except near branching points, the neutron capture reactions are in flow equilibrium with the β decays (This might incur larger uncertainties on the weak *r*-process component, for this reason.). Little detail needs to be assumed about the astrophysical reaction environment. These model calculations then can be calibrated, or normalized, to observational data with great reliability. This is particularly true because a number of stable isotopes away from the valley of stability and toward the neutron rich side provide shielding against the *r*-process path and its contributions. Thus one can fit the parameters of the model to best represent this set of about 35 isotopic abundances of *s*-only nuclei. (See discussions of different methods by Arnould et al. [403].)

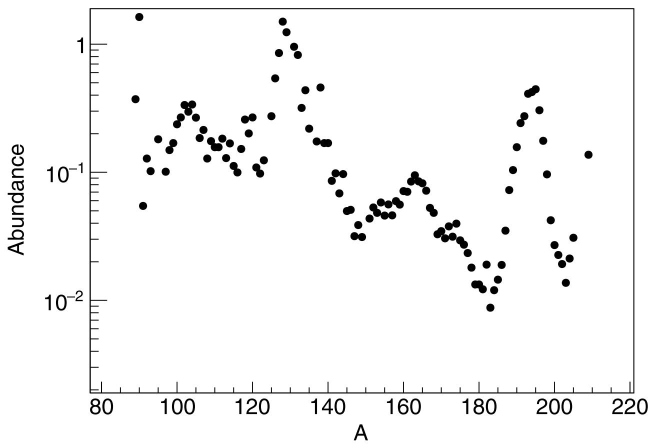

Fig. 6. Solar system isotopic abundance pattern.
Source: From [426].

This enables an estimation of the fraction of abundances produced by the *s*-process for other nuclei [429]. The *r*-process component of each isotope is then determined by subtracting the *s*-process component from the abundance of each isotope for solar-system material. The contribution of the *s*-process to solar abundances of elements heavier than iron has been determined to be about two thirds overall, with specific element contributions of 85% for barium (a typical *s* element) and 6% for Europium (a typical *r* element) [426,430]. Nevertheless, this derivation of the *r*-process abundances is not without problems: Strictly speaking, those abundances are just the "not from the *s*-process" abundances, and could be a combination of nucleosynthesis processes (and sites).

The uncertainty of the *s*-process models affects the accuracy of the estimates of the *r*-process abundance patterns of solar-system material. This is particularly significant, or even dominant, in the case of the nuclei in which *s*-process contributions dominate. This is because a small error in the estimate of the *s*-process component can result in a large error in the obtained *r*-process fraction. One example is the element Pb (*s*-process third peak). For this element the *s*-process component should be dominant in solar-system material. On the other hand, a pure origin from the *r*-process cannot be excluded. The production of Pb by the *s*-process is dependent on models and is not well estimated from other elements. This makes it difficult to constrain the models for production of heaviest stable nuclei by the *r* process [403,426], due to the absence of sufficient *s*-only nuclei for model calibration in this region. Also, tracing the uncertainty of the "*r*-process abundances", one must properly add the uncertainty of the primary isotopic abundance to the uncertainty of the model fit, plus the uncertainty of the neutron capture cross sections that are inherent in the model.

Solar abundances are determined from photospheric absorption line spectroscopy [431,432] and from meteoritic sample analyses [433]. An essential contribution from the analysis of meteorites is that it can determine isotopic abundances and ratios. This is the basis of the above constraints on the models for the *s*-process. Recent assessments of the two methods exhibit fairly good agreement for heavy neutron-capture elements in general [432]. In particular, the updates of atomic-line data, including the effects of hyperfine splitting and isotope shift, contributed significantly to the improvements of the estimates of the solar *r* abundances [e.g. 434].

5.3. Observing an r-process event

5.3.1. Gamma rays from radioactivities

Characteristic γ rays from radioactive decays could be the most-direct measurement of decay, and hence of freshly-injected nuclei, from a source. The line energy characterizes the isotope, and the intensity of the decay marks and supports the assignment to a particular isotope [416].

Most likely, γ ray emission will be dominated from the decay of isotopes that are close to the valley of stability, rather than the ones close to the *r*-process path. This is because isotopes along the *r*-process path are expected to be very short-lived. The nucleosynthesis during the *r* process is derived from nuclear-reaction network calculations. Measurements in laboratories can be made of the level schemes that might be populated along the β decay sequence as it approaches its end near or at stability of the daughter isotope. This provides estimates of the characteristic γ-ray spectra [435].

Knowing the line energy, spectrometers with adequate resolution are able to set much more direct constraints on the composition of material created in the event. This is better than absorption line spectroscopy from atomic lines resulting from the transport of γ-rays of the radioactivity from thermalized photospheric gas. Sensitivities of current γ ray spectrometer instruments are about 10^{-6} ph cm^{-2} s^{-1} for observing times of 10^6s. This provides a window of opportunity only for radioactive isotopes with decay times below several weeks, and for sources ejecting $10^{-3}M_\odot$ of such material at about 5 Mpc distance. The *r*-process events are plausibly rare. Therefore, no such gamma-ray signal has been seen. The chance to detect a nearby event would be low at the required rates below a few Mpc^{-3} yr^{-1}.

5.3.2. Kilonova emission and GW170817

The key to a successful broad observational dataset for a single source event was the GRB trigger detected by Fermi and the followup search for the characteristic and unique chirp signal of gravitational wave emission, as it emerged from the collision of two neutron stars. On August 2017, the LIGO and VIRGO gravitational-wave facilities reported such a signal [14], which led to a wide range of follow-up observations. The coincident detection of a γ-ray burst signal of the 'short' type by the Fermi-GBM and INTEGRAL/SPI gamma-ray instruments [436,437] provided more clues as to the nature of the event. These supported the earlier hypothesis that sGRBs originated in neutron star mergers. Several hours were necessary to digest the significance of those two event triggers and their apparent correlated nature. Then a fleet of optical telescopes and other facilities were ready to follow up on the event (as it had been daytime in Chile when the event occurred). An electromagnetic signal attributed to the event was detected with GROND and other telescopes and attributed to the same event [438]; this signal is called a *kilonova*, from its brightness ranging between that of novae and supernovae. The distance to the event then was estimated to be 40 Mpc, from the association of the kilonova with the elliptical galaxy NGC4993. The light curve and spectra obtained from these observations provided a hallmark for the study of neutron star mergers, as well as for the study of the origins of the *r* process. They showed a characteristic decay of the kilonova within a few days, consistent with radioactivity as the source of energy heating the kilonova (see Fig. 7).

The spectrum peaked in the infrared regime around 1–2 μm, which hints at envelope material rich in heavy elements and with a large UV/optical opacity of light that characterizes GRBs/SNe [421]. With the spectrum, broad features can also be recognized. These are reminiscent of the lines of heavy elements Doppler-broadened by ejection velocities of order 30% of the speed of light. Note, however, that the wavelengths, transition probabilities, and branching ratios of *r*-process elelments are very poorly known, such that it is presently practically impossible to build realistic synthetic spactra. In particular, the presence of broad features that result from a few lines is physically impossible unless those lines are very strong, which may not be the case for *r*-process elements, casting significant doubts on existing tentative identifications. Alternatively, the superposition of many lines could give rise to broad features, though the properties of enough lines of different elements or ions to support such statements are not known well enough, as a large number of lines originate from typically 90 – 110 atomic-shell electrons [e.g. 439]. Therefore, improvements of radiation transport models as well as atomic physics knowledge of heavy elements are required, before such associations can be claimed.

Nevertheless, the observations of the overall spectral energy distribution appear plausibly consistent with expectations from the kilonova model [439]. Upon more detailed comparison to models, it turns out that the electromagnetic emission is more persistent and brighter than predicted in models, particularly in the red part of the spectrum. This might be due to a relatively-large aspect angle, compared to the jet axis. Such a jet is also expected to represent the main direction of bright gamma-ray emission from the associated short GRB. (See Burgess et al. [440] for a detailed discussion on the GRB emission and its puzzles.) At large aspects, the ejecta from a neutron star merger are a mixture of dynamical ejecta as the neutron stars collide, disk wind ejecta as the black hole forms, and the unbound torus with nucleosynthesis enrichments. (See Rosswog et al. [441] and Metzger [442] for phases of neutron star merging and material ejection, which emphasizes nuclear reaction network calculations in 1D and 3D. Also see Mazzali et al. [443] for an accurate treatment of energy deposition and reradiation, which - while used for SNeIa - is also important for kilonovae.)

Clearly, more such events would need to be studied from observations and models, to disentangle the aspects of different ejecta and nucleosynthesis, as they appear from different viewing angles. Nevertheless, as in the case of supernovae, much can be learned from spectroscopy of the subsequent emitted light. Supernova studies of radiation deposits and re-radiation have paved the path toward these studies. (See Kerzendorf and Sim [444] for a recent model.)

5.4. Metal-poor stars in our galaxy

Currently, there are about 1000 metal-poor stars in our Galaxy for which measurements of most of the elemental abundances have been obtained [400]. Fig. 8 shows the abundance distribution for Fe and Ca for example. The abundance patterns of such metal-poor stars are very useful references to study the yields of the sources of the *r* process and their possible variation [402]. Details about the abundance distributions are discussed in Section 5.4.2.

5.4.1. The abundance pattern in the stellar archeological record

Photospheric spectroscopy has established that in a subset of metal-poor stars, heavy element abundances appear to be enhanced relative to general metallicity. (We take metallicity as indicated through the iron elemental abundance). Fig. 8 depicts Eu abundance of Galactic stars versus the Fe abundance. Since Eu is most-easily measurable among elements whose origin is predominantly *r* process, Eu-enhanced metal-poor stars found in [Fe/H]< -2.5[1] in the figure are ideal objects to study the abundance patterns produced by the *r* process. Fig. 9 shows a typical example of such an elemental abundance pattern [400].

A surprising result obtained for Eu-rich stars from the early studies of such objects is that the abundance patterns of neutron-capture elements of these stars are very similar to that of the *r*-process component in solar-system material [402,446]. The agreement is in particular evident in elements from the second and third peaks corresponding to neutron magic numbers 82 and 126 (Ba-Pt). We note that the measurements of the elements at the second *r*-process peak (for

[1] Abundance ratios of two elements are given as $[A/B] = \log(N_A/N_B) - \log(N_A/N_B)_\odot$. [Fe/H] is referred to "Fe abundance".

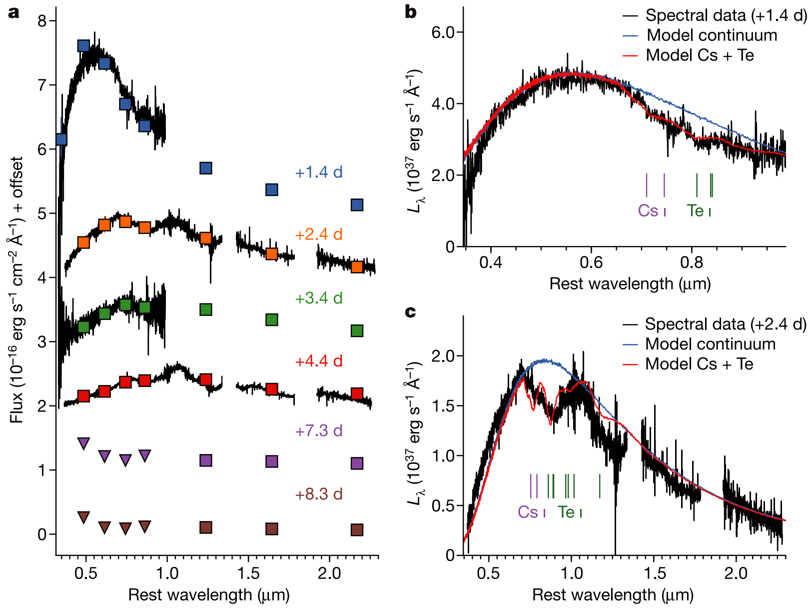

Fig. 7. The spectrum of the neutron star merger event GW170817 shows a characteristic decline from radioactive energy deposition, re-radiated by envelope material in optical and infrared emission. The spectrum peaks at around 1 μm wavelength, which is thought to reflect a composition rich in heavy elements. Suggestive features may indicate the presence of Cs and Te, although the line signatures of heavy elements are quite uncertain. *Source:* From Smartt et al. [394].

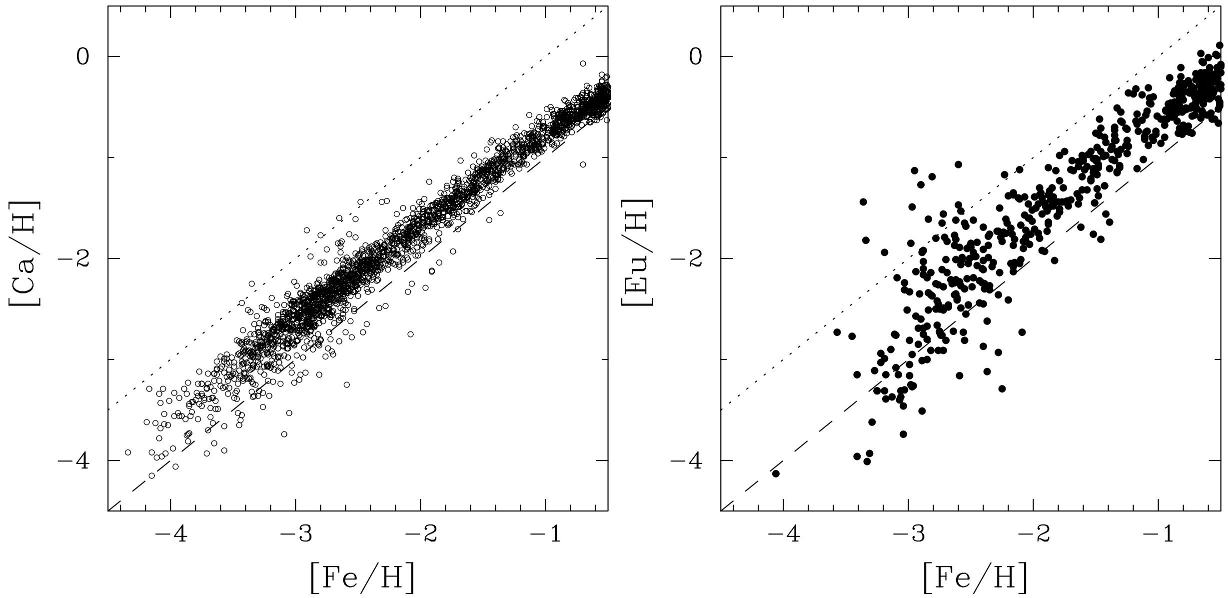

Fig. 8. Abundances of Ca and Eu as a function of Fe abundance in Milky Way field stars. Abundance data are taken from the SAGA database [445]. Dashed and dotted lines indicate [X/Fe] = 0 and 1, respectively, for X = Ca and Eu. Dozens of stars with [Fe/H]~ -3 show enhancement of Eu ([Eu/Fe]$> +1$).

a Te detection) are only available by UV spectroscopy with the Hubble space telescope (HST) for a few of the brightest stars [447].

Fig. 9 also shows the 'solar *r*-abundance pattern' for comparison (black solid line). The residuals (lower panel) indicate that this pattern is reproduced in many metal-poor stars, although for the light *r*-process elements, the larger residuals indicate more variety. Although data still are sparse, from few Te data points, the heavy *r*-process pattern is believed to be rather robust. Compared to the elements from the second and third peaks, abundances of lighter elements show star-to-star scatter. This could be due to the variation of the abundance pattern produced by the *r*-process event. There

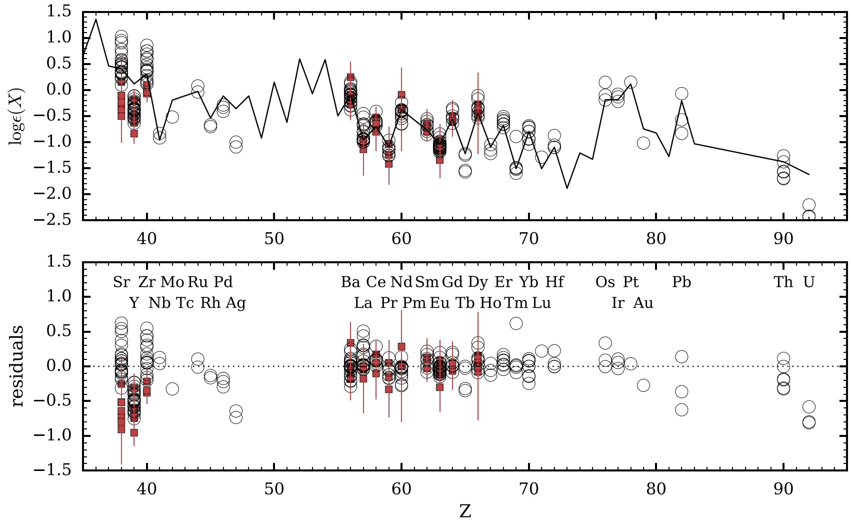

Fig. 9. Elemental abundances pattern characteristic of the *r* process. Open circles show data from halo stars, red boxes are data from stars in dwarf galaxy Ret II. The black line shows the scaled solar abundance pattern after subtraction of the s process abundances.
Source: From Frebel [400].

could also be contributions of another *r* process that provides light neutron-capture elements in the early Galaxy (see Section 5.4.3).

Another interesting result is the abundance variation of actinides, Th and U. The abundance ratios of these elements with respect to the second-peak elements such as Eu are generally lower in very metal-poor stars, as expected from their decay since these stars are older than the Sun (Fig. 9). However, some objects have excess of Th compared to the expected value from the solar-system *r*-process pattern (including the decay effect), and are called *actinide-boost* stars [448].

The variation found in the current sample of Eu-enhanced stars is, however, at most a factor 0f three, whereas the production of actinides is predicted to be severely dependent upon parameters in the *r*-process models. This result suggests that the abundance ratios of actinides produced by the *r* process in the early Galaxy are *regulated* by some mechanism. Another observational part of the *r*-process puzzle is the relatively low abundances of Pb compared to actinides (Fig. 9). Since Pb is the product of the decay of actinides and other heaviest nuclei, it is difficult in the models to reduce the Pb production while keeping the abundance of actinides. Hence, possible problems in abundance measurements for Pb need to be considered [449].

5.4.2. Abundance pattern variabilities

The trends and scatter in the Eu abundance distribution shown in Fig. 8 also provide a useful constraint on the origins of the *r* process. The enrichment of an element depends on the time scale for the corresponding nucleosynthesis event.

A recent, very precise ($\sigma \sim$0.01 dex), determination of elemental abundances for 12 elements has been obtained for 79 solar-twin stars at different metallicities [450]. This not only sets the abundances, but it also allows for tracing the galactic evolution over 10 Gyr, even separating thick and thin disk aspects. From their analysis, the authors conclude that in the thin disk *s* process contributions prevail during the entire history of the Galaxy, while in the thick disk, enhancements from the *r* process are clearly a characteristic common feature. This suggests that in the early galactic evolution, the *r* process was highly active [450]. In the more metal-poor stars of the Galactic halo, the main source of neutron-capture elements was from the *r* process.

A remarkable result obtained by the intensive spectroscopic studies for very metal-poor stars in the past two decades is the discovery of large star-to-star scatter in abundance ratios of neutron-capture elements. Fig. 8 shows the Ca and the Eu abundances as a function of metallicity (Fe abundance). Here we adopt Eu as an indicator of the *r*-process yields. We find a clear correlation, with little scatter, in the abundances between Ca and Fe. Both of these originate from massive stars and their supernova explosions at low metallicity. Contributions of type Ia supernovae are significant at high metallicity, and result in a change of the slope for [Fe/H]> -1 (see next section). In contrast to the Ca abundances, the Eu abundances show a large star-to-star scatter at low metallicity. The object having the highest Eu enhancement with respect to Fe has [Eu/Fe]$\sim +2$ [93]. Metal-poor stars with high Eu abundances are interpreted as objects that were born from gas clouds significantly polluted by an *r*-process event in the early Galaxy. This indicates that the gas clouds were not chemically homogeneous, and insufficient mixing appears to be a characteristic of the early Galaxy. The *r*-process events should then be only weakly coupled to those providing Fe, which in the early Galaxy would be the common core-collapse supernovae.

Recent studies suggest that *r*-process-enhanced stars have been formed in small stellar systems such as the currently observed ultra-faint dwarf galaxies. These probably were enriched in heavy elements only by a small number of *r*-process events (see next subsection).

The detection probability of Eu is lower in metal-poor stars having a low Eu abundance, because Eu spectral lines are quite weak in such objects. The fraction of r-process-enhanced stars is estimated to be about 3% including this bias [451]. This indicates that the Eu-producing r-process events are rare, but each event could provide the Galaxy with a large amount of Eu.

5.4.3. Light neutron-capture elements

The universality of r-process abundances does not seem to extend over the entire range of elements heavier than Fe-group elements. In general, the lighter of the heavy elements, in the Sr–Y group (see Fig. 9) conform less to the solar r-process pattern. The abundance of the even lighter element Ge does not correlate well with Eu, and may indicate a special, i.e. non-r process, origin for Ge, although measurements of this element are limited to a small number of metal-poor stars.

On the other hand, there are many metal-poor stars that have low abundances of heavy neutron-capture elements like Eu, but have a large excess of light elements [452,453]. The origin of the excess of these lighter elements is still a controversy, and is sometimes attributed to a *Light Element Primary Process* [7] or *weak r process* [427]. Continuous observational studies have been made to reveal the characteristics of this process. A recent study [454] shows that metal-poor stars have wide variations in the abundance patterns from light to heavy neutron-capture elements including intermediate ones (e.g., Mo, Pd). A correlation of the Mo ($Z = 42$) abundance to those of Sr, Y and Zr ($Z = 38$–40) was reported along with a gradual decrease of abundances with increasing atomic number.

5.5. Stellar abundances in other galaxies

Small stellar systems, dwarf spheroidal galaxies, are found near the Milky Way Galaxy, sufficiently close so that interactions with the Galaxy are plausible. These have a wide range of stellar mass (10^3–10^7 solar masses), and are characterized by an absence of interstellar gas. Their stellar population thus has formed long ago, and probably in the early evolution of that system. They could be survivors of small stellar systems born in the very early phase of the Milky Way formation. About 30–40 such galaxies are known at present. Such small stellar systems could be significantly affected by a small number of nucleosynthesis events. Therefore, even a single r-process enrichment might be revealed in observations of metal-poor stars from nearby dwarf galaxies. Accretion of such stellar systems could be the origin of the r-process enhanced very metal-poor stars in the Milky Way halo. Therefore, they are a useful complement to r-process studies from stars in the Milky Way galaxy.

Fig. 10 compiles the Eu abundances measured for dwarf galaxy stars. As in the case of galactic field and halo stars, generally, the Eu abundances increase with an increase of Fe abundances. The number of stars with low Eu abundances at low metallicity ([Fe/H]< -2) is small, compared to Galactic field and halo stars shown in Fig. 8. This, however, reflects a bias in the sampling due to the less-sensitive detection limit of Eu lines for dwarf-galaxy stars, which are apparently much fainter than field halo stars studied with high-resolution spectroscopy.

It is remarkable that dwarf galaxy stars with $-2 \lesssim$ [Fe/H] $\lesssim -1$ have almost constant [Eu/H] values (~ -1.3), independently of their Fe content [455]. Subsequent observational studies for a larger sample of dwarf galaxies further support this feature [455,456]. It appears that particular and large enrichment from the r process has occurred early, while later evolution increases both Fe and Eu as found in Fornax stars.

The dwarf galaxy Reticulum II appears to be a unique object. Here, an entire group of very metal-poor stars ($-3 \leq$[Fe/H]< -2.5) show a surprisingly large excess of Eu that is about 1–2 orders of magnitude higher than that seen in other dwarf spheroidals [398,399]. At first glance, this appears to reflect a massive and single r-process enrichment event, providing the seed for the material out of which all these stars formed in an early phase of the evolution of this galaxy when [Fe/H]~ -3 or -2. Such Eu-enhanced stars are also known in the Milky Way halo, as mentioned above, and here their fraction is estimated to be about 3% [e.g. 451,457]. In Reticulum II, abundances were measured for nine stars that must have formed early at low metallicity ([Fe/H]< -2), and seven of them have high Eu abundances. The remaining two stars have the lowest metallicity ([Fe/H]< -3) of the observed sample. Hence, these may have formed earlier. A large set of 41 elemental abundances in the brightest star of Reticulum II at a visual magnitude of 16 were measured, improving precision in this case by a factor 2 [399]. This study confirms a general r-process enrichment with the known abundance pattern, including abundances up to the third r-process peak. Eu abundances in r-process-enhanced stars in faint dwarf galaxies including Reticulum II are found at values [Eu/H]~ -1.3. This corresponds to a Eu/H mass ratio of $10^{-10.6}$. Assuming the original mass of hydrogen gas in the galaxy to be 10^6 solar masses, this yields an Eu mass estimate to be provided by the r process of $10^{-4.6}$ solar masses. This almost constant value of Eu abundance could be explained if the supply of r-process elements is due to a single event in an early evolutionary stage of these galaxies. Moreover, the amount of Eu is comparable with the expected r-process products of neutron star mergers [428].

5.6. Abundances of interstellar gas in the galaxy

Interstellar gas assembles the ejected material from individual nucleosynthesis events, including that of the r process. The stellar abundance measurements discussed above assume that the stars being observed formed out of material that either was sufficiently mixed to represent the chemical composition of the star forming region at that time, or else had a special enrichment from a single, additional, r-process injection event (for the 'r-enriched' abundance results).

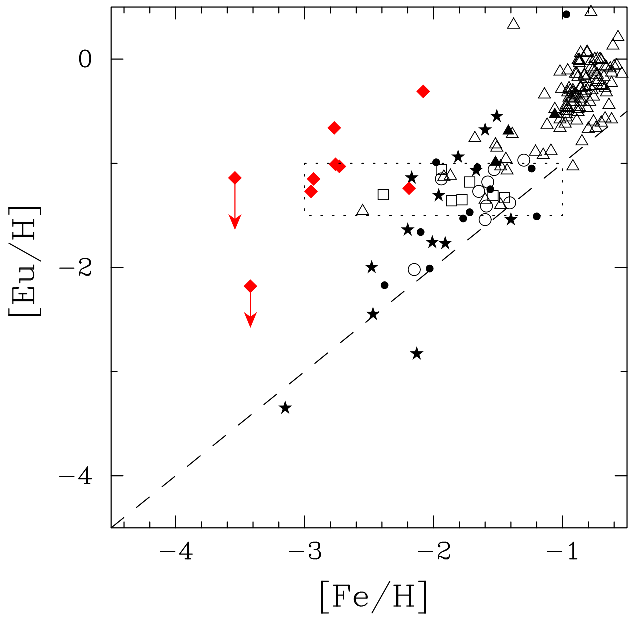

Fig. 10. Eu abundance ratios of stars in dwarf galaxies as a function of metallicity ([Fe/H]). Abundance data are taken from the SAGA database [445]. Different symbols mean stars in different galaxies (open triangle: Fornax; open circle: Carina; filled circle: Sculptor; open square: Draco; filled triangle: Leo I; stars: Ursa Minor; red filled diamonds: Reticulum II). Upper limits of Eu abundances of the two most metal-poor stars in Reticulum 2 are also shown. The other seven objects in Reticulum II are very metal-poor but show large excess of Eu. A typical error of [Eu/H] is 0.2 dex, although it depends on data quality and strength of spectral lines. The dashed line indicates [Eu/Fe]= 0. Many metal-poor stars in faint dwarf galaxies have similar [Eu/H] values around −1.3 (box shown by dotted line).

Mixing of interstellar gas is believed to be driven by turbulence created by winds and explosions, mostly, with some low-frequency contributions from large scale kinematics and spiral wave transits. But since injection of fresh nucleosynthesis material probably occurs where the interstellar gas is being energized and heated, the process of star formation generally requires interstellar gas to be cold so that gravitational attraction can form dense (protostellar) clumps within molecular clouds. In between, therefore, interstellar gas is required to both mix and cool. Typical times discussed for this are on the order of 10^5 to 10^8 years. With a supernova rate on the order of 10^{-2} y^{-1} in our Galaxy [458] within such settling time of freshly-enriched interstellar gas, there is a significant probability of other supernovae occurring. Specifically, these would be from massive stars, which generally are produced as a group and hence in the same region. Therefore, multi-event enrichments appear plausible before stars are being formed, with a corresponding bias. It is therefore (i) not surprising to find differences in compositional signatures between stars and gas, and (ii) rare nucleosynthesis events and their enrichments may be more easily recognized in stellar material, as anomalies from the well-mixed and multiple-source averaged typical stellar abundance signature.

On the other hand, the available abundance data from interstellar gas includes its own bias and systematics. In particular there are biases from pre-solar grains, terrestrial deposits, and emission line physics. Absorption line spectroscopy against background sources such as stars, AGNs, and gamma-ray bursts are scarce, but will provide a useful complement to such data. ALMA is going to play an important role here [459].

5.6.1. *r*-Process material on earth

Material on Earth also can provide astronomical, or cosmic, information, if anthropogenic distortions can be separated or eliminated. The field of nucleo-cosmochronology has been established from the study of long-lived terrestrial radioactivity [461] as was originally suggested by Rutherford in 1929. This made use of the U and Th radioactive decays to estimate, on one hand, the epoch of their nucleosynthesis long before the solar system formed (if isotopes of the same element are used), and, on the other hand, the production ratio of U/Th, can constrain the *r* process itself.

An interesting current-day *astronomical* measurement is added from material that falls to Earth, if as is the case for pre-solar grains (see below), and for material that can be excluded to arise from cosmic ray spallation reactions. The latter is the case for all nuclei well above the iron group and specifically abundant ^{54}Fe. Even terrestrial ^{60}Fe thus provides information on supernova nucleosynthesis, and has been measured in ocean-crust deposits and lunar samples. However, we do not discuss this here, as ^{60}Fe plausibly is attributed to the *s*-process. Ocean crust material has been shown to slowly accumulate material from the Earth's atmosphere, cosmic-ray age dating of depth layers thus establishes a record of infalling interplanetary gas over millions of years. The probes taken from locations distant from coastlines and at great depth (thousands of km, and >5 km, respectively) have been shown to be free from contamination, and thus suitable for

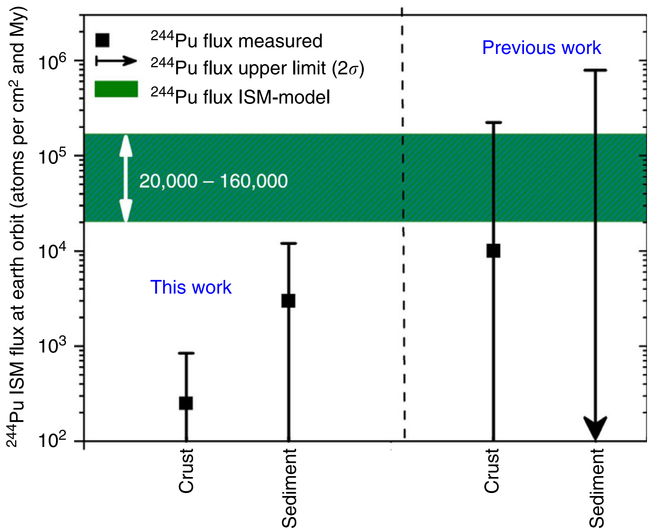

Fig. 11. The rate of events injecting ^{244}Pu into the terrestrial atmosphere.
Source: From Wallner et al. [460].

study. Most interesting for the *r* process is ^{244}Pu with a radioactive half-life of 81 million years. After several searches in 2015 the method of accelerator mass spectrometry obtained a signal that could be combined with other deposits to yield an incident flux of ^{244}Pu at Earth from currently-active *r*-process nucleosynthesis [460]. Fig. 11 shows this result, as compared to the core-collapse supernova injection rates derived from earlier measurements. The predictions are shown as the horizontal (green) band. The tacit assumptions are that interplanetary dust particles reaching Earth are representative of the current interstellar medium composition in the solar vicinity, and that this is sufficiently well mixed to represent nearby nucleosynthesis over the past 10^8 years. Expectations can then be set from the Galactic rate of core collapse supernovae of about 1–2 per century [458], if one (the most-frequent) *r*-process scenario is used as a reference. Wallner et al. [460] show that the measured rate falls 2–3 orders of magnitude below such expectations. This clearly implies (within the above assumptions) that the rate of nearby *r*-process events must be much smaller than the rate of supernovae.

As discussed by Hotokezaka et al. [462], the abundance of ^{244}Pu ($T_{1/2}$ ∼81 My) also available at the time of solar system formation, provides information. Its relatively large abundance relative to ^{238}U ($T_{1/2}$ ∼4.5 Gy) suggests that at the time of solar system formation, an *r*-process injection into the proto-solar molecular cloud occurred within ∼100 My, while currently the above mentioned ocean crust value suggests a lower rate.

This early solar system presence indicates that the *r* process did indeed occur in the solar vicinity at the time of solar system formation, The universality of the *r*-process abundance pattern suggests it was ongoing from the epochs of the young Galaxy until solar system formation (see however late injection scenarios discussed for the early solar system, [e.g. 463].) Tsujimoto et al. [456] provide an analysis of all available radioactive clocks which may be used to constrain the heavy-element injections into the proto-solar nebula, and hence in meteoritic material. They then separate an 'average' from a 'latest-event' injection, comparing the different heavy-element abundances. Thus, they derive a constraint on the rate of *r*-process injections relative to the rate of supernova material injections. Their value of 1/1400 requires that *r*-process injections are rare, compared to supernovae. Rare variants (at a level of 10^{-3} or below) of supernovae, and also neutron star mergers, can fulfill both of these constraints.

We note, however, that the conversion of the ocean crust measured count of ^{244}Pu atoms to an ejected amount of ^{244}Pu from a source involves several steps. Each of these has considerable uncertainty: (i) The conversion to ^{244}Pu flux incident on the top of the Earth's atmosphere involves ocean and atmospheric transport; this is probably well calibrated through ^{10}B and ^{53}Mn, which are produced by cosmic rays in the upper atmosphere, and the uptake factor for the deep ocean probe can be measured. (ii) The transport of interplanetary dust particles, the presumed carriers of ^{244}Pu, in the heliosphere and a Local Bubble is uncertain. Magnetic fields and the net electric grain charge will be key. Additional steps not only involve the ocean crust constraint, but, in the same way, the constraints that can be derived from meteoritic analyses and of early solar system material: (iii) The transport of nucleosynthesis ejecta into the interstellar medium, and into the Local Bubble, therefore, involves (a) the physics of the turbulent and dynamic interstellar medium, and (b) the initial slowing down and cooling of hot matter by the ISM.

The first aspect (a) is being addressed by magneto-hydro-dynamical simulations [e.g. 464], and turns out to be a major astrophysical challenge, across scales beyond a few hundred parsecs. Then, one may adopt different locations of the solar system within the ISM structures, leading to a variety of conditions as shown by Kuffmeier et al. [465] for the case of the ^{60}Fe/^{26}Al ratio from supernova nucleosynthesis. The second aspect (b) may be explored from supernova remnant observations. Tracing ejecta flows into the ISM can be done through radioactivity studies. Typically, supernova remnants show observable characteristics in radio and X-ray emission from young ages until several tens of millenia. But this does not imply ejecta mixing within 10^5 y or thereabouts. Only the particle energies fall below the radio and X-ray emission thresholds. Tracing γ-ray emission from radioactive ^{26}Al ($T_{1/2}$ ∼700,000 years), the large Doppler shift velocities exceeding typical galactic rotation [425] have been interpreted as an indication that nucleosynthesis from massive stars and their supernovae are typically injected into kpc-sized superbubble cavities [466]. Multiple such injections of nucleosynthesis ejecta would occur into the same superbubble. Therefore, mixing could be delayed by the fate of the superbubble's evolution. Then, cooling of fresh ejecta may not occur on time scales below 10^8 y. Thus the composition of material would be better characterized by the mixing properties of the ISM, than by the rate of injection events.

Clearly observations of terrestrial material are proof that ^{244}Pu abundances are not a sample of what is called the generic *r*-process abundance pattern. This could be related to nucleosynthesis transport in the interstellar medium, or to scarcity of nucleosynthesis injections.

5.6.2. Constraints from pre-solar grains

While the analysis of the isotopic composition of material samples in the laboratory clearly obtains the most precise values for abundances among different elements and isotopes, the path from cosmic interstellar gas to the terrestrial laboratory includes numerous possibilities to affect the composition. The first step is the formation of dust grains. This requires appropriate thermodynamic conditions, as chemical reactions to operate for sufficient time to form molecules that are refractory, and nucleation to form a dust grain.

Grain surface chemistry is then important to the composition of interstellar gas in its cold phases, and ice mantles of specific species (water, ammonia) may grow to make larger grains. Interstellar grains, unlike gas, then propagate ballistically, although the grains are not electrically neutral due to their higher mass. In the interstellar medium, shocks and radiation from nearby stars heavily processes dust. This may fragment grains, remove ice mantles, and generally change the grain size distributions. For most of these processes, the isotopic composition of an element is rarely affected, with exceptions from isotope-sensitive chemical reactions of light species. Therefore, nucleosynthetic studies on material samples of pre-solar origins require normalization. Deviations of isotopic ratios within an element from the solar reference are the key information.

In early analyses of meteoritic material, such deviations had been interpreted as a general indication that the meteoritic material included an unknown and variable contribution of pre-solar grain material. The deviation from solar isotopic ratios could be attributed to isotopic under- or over-abundances in pre-solar grains, as the contamination fraction and origin varied. Only with the development of nanometer scale spatial resolution of laboratory mass spectrometry could determine multiple isotopic ratios for individual pre-solar grains became possible. The harsh chemical sample preparation for such analyses includes chemically dissolving much of the bulk meteoritic material, leaving behind the most refractory parts. This led to the isolation of stardust grains in the forms of diamonds, silicon carbide, and graphite grains [e.g. 467].

Generally, presolar grain composition analyses have failed to show clear evidence of any *r*-process contributions [468]. While some anomalies exist for Xe, Mo, and Ba isotopic ratios, the case for a clear signature of a rapid neutron capture origin is too uncertain at least for Ba and Mo: Barium in general is considered a typical s process product, as all stable isotopes lie along the region of stable isotopes with no unstable isotope in between, and only shielding from the *r*-process path by ^{134}Xe and ^{136}Xe plausibly can imprint *r*-process information for these s-only isotopes. These are superimposed on a mix of r and s process origin for the other isotopes. In the case of ^{100}Mo, only one unstable isotope separates this isotope from the valley of stability, and episodic strong neutron irradiations in shell burning regions of massive stars have been invoked to explain the abundance deviation of ^{100}Mo [469]. The Xe isotope abundance pattern, finally, appears to be the only clear *r*-process signature from pre-solar grains. However, the absence of a similarly-high excess in the ^{136}Xe abundance is puzzling, and requires a specific explanation for attribution of the Xe abundance signature to be related to *r* process [470].

5.7. Astronomical summary on the r process

The elemental-abundance pattern seen in the currently-available sample of heavy-element enriched metal-poor stars of our Galaxy is remarkably reminiscent of the abundance pattern seen in solar material after subtraction of the (modeled) contribution from the *s* process. This suggests that some *r-process* nucleosynthesis has been operating in the Galaxy since its earliest evolution and until today.

The observed scatter in abundances of *r*-process elements appears significantly larger than the observed abundance scatter for elements attributed to massive stars and their supernovae, and to supernovae of type Ia. Thus, it appears as if normal supernovae of any of the two major types are not the sources of the *r* process. Rather, events that occur at substantially lower frequency, and/or mix significantly less-well with star-forming interstellar gas in the Galaxy, must be responsible for providing material from the *r* process. The observed low content of ^{244}Pu, as compared to ^{60}Fe, in ocean crust material on Earth points in the same direction, i.e., ^{244}Pu-contributing event and less frequent or less efficient deposits of interstellar material within the current solar system. Also, an apparent enrichment in heavy elements by a rare, probably single, event in one of the small satellite galaxies of the Milky Way galaxy point to a source of the *r* process that occurs at a rate well below 10^{-4} yr^{-1} and ejects on the order of 10^{-4}–10^{-2} $M_\odot$ of material enriched in *r*-process nuclei.

The neutron star merger event GW170817 and its kilonova have contributed valuable and detailed data from a currently most-plausible source of *r*-process material. The spectrum of the kilonova light and its rapid fading in brightness are consistent with models which have an *r* process which has synthesized radioactive material and ejected heavy elements as a key ingredient.

No further *r*-process relevant observations could be contributed to date from pre-solar grain or gamma-ray line studies. Nevertheless, in principle, these are promising candidates for measuring the signature of an *r* process rather directly, i.e. as isotopic information.

6. Sites for the *r* process

There are a number of viable sites that may satisfy the basic requirements to enable an *r* process (as discussed in Section 4 above). They each are likely to contribute at least some to the total abundance of *r*-process elements in the Galaxy [e.g. 11]. In the following sub-sections we give the essential ingredients in a number of candidate models, and we summarize their respective status on the basis of the current literature, then discuss their weaknesses and strengths in the light of the observational constraints.

6.1. Neutrino driven winds

A favored model for *r*-process nucleosynthesis for a number of years was the neutrino driven wind (NDW) above the newly formed proto-neutron star in CCSNe [12]. A neutron star is formed by the collapse of the iron core of a massive star. The proto-neutron star then cools by the release of $\sim 10^{53}$ ergs in neutrinos on a timescale of $\sim$10 s. These neutrinos interact with material behind the outgoing supernova shock. This generates a hot bubble that helps to drive the explosion [471,472]. It also leads to the ablation of material from the proto-neutron star into the hot bubble. This is the so-called neutrino-driven wind (NDW). The high entropy and large number of neutrons per seed in this wind seemed at one time to be an ideal *r*-process site [12]. Neutrino nucleus interactions, however, are key [473] to the success or demise of this model.

Although the original formulation was quite successful, subsequent calculations [474–478] have found the NDW to be inadequate as an *r*-process site. The downfall of the NDW has been attributed [474,476] to the implementation of higher-order modern neutrino transport methods, and effects of the neutron–proton mass difference. These cause the neutrino luminosities and energies to diminish at late times. The resulting electron fraction and neutrons per seed ratio in the neutrino driven wind become too small for a robust *r* process, although this can be mediated somewhat by nuclear medium effects on the neutrino opacities [479]. Another difficulty is the alpha effect: In a core-collapse supernova during the epoch of alpha particle formation as the temperature drops protons produced by ν_e capture on neutrons can in turn capture more neutrons to bind into alpha particles, increasing the electron fraction [480]. This "alpha effect" could be a significant impediment to achieving the required *r*-process yield [481]. Density fluctuations may amplify this effect [482]. However, it is possible to get around the alpha effect by assuming presence of sterile neutrinos which reduce the ν_e flux [483–485].

There is also some indication [486] that the diminished neutrino luminosities depend upon nuclear equation of state as well. Neutrino luminosities and energies were studied for variety of Skyrme density functional equations of state in [486]. These were chosen as they are consistent with constraints on the symmetry energy from the combination of isobaric analog states, pygmy resonances, and heavy ion collisions and also satisfy neutron stars with masses as large as 2.01 ± 0.04 $M_\odot$ as required by observations [487,488]. For all of these models a drop in the late time neutrino energies and luminosity results even in a low order multi-group flux-limited diffusion scheme. Hence, the likelihood of a NDW *r* process seems less likely in the current models for core-collapse supernovae.

The desired conditions of high entropy and neutron-rich composition [478,489] do not occur in standard neutrino energized wind. Nevertheless, it is quite likely that a *weak r process* occurs in the NDW producing neutron rich nuclei up to about $A \sim 125$ [11,478].

6.2. Magnetic neutrino-driven wind

Although standard models of neutrino-heated winds from proto-neutron stars do not reach the requisite neutron-to-seed ratio for the production of *r*-process nuclides beyond the $A \approx 130$ peak, the abundance distribution created by the *r*-, *rp*-, or νp-processes in proto-neutron star winds depends sensitively on the entropy and dynamical expansion timescale of the flow, which may be strongly affected by high magnetic fields.

Thompson and ud-Doula [490] performed magnetohydrodynamic simulations of nucleosynthesis for non-rotating neutrino-heated winds from proto-neutron stars with strong dipole magnetic fields (10^{14}–10^{16} G). It was found that the strong field forms a closed zone and helmet streamer configuration at the equator, with episodic dynamical mass ejections in toroidal plasmoids. This dramatically enhanced the entropy in these regions and conditions favorable for the production of the third-peak *r* process could be obtained if the wind was neutron-rich. For $B \gtrsim 10^{15}$ G, it was found that $\gtrsim 10^{-6}$ $M_\odot$ and up to $\sim 10^{-5}$ $M_\odot$ of high entropy material was ejected per highly-magnetized neutron star birth in the wind phase, providing a possible mechanism for prompt rare heavy element nucleosynthesis even in the neutrino-driven wind scenario.

6.3. r-process in low-mass prompt supernova explosions

One of the earliest numerical supernova models for the *r* process [491] was based upon the shock-induced ejection of neutron-rich material in low-mass ($\sim$10 $M_{\odot}$) core collapse supernovae. Although this model is not often referenced in the literature of the past decade, it remains as a viable model for the *r* process [492,493].

Among core-collapse models, low-mass O-Ne-Mg cores are the easiest to explode [494–496]. They have smaller cores and weaker gravitational potentials, and are in nuclear statistical equilibrium at the time of core bounce. As such, these stars have the possibility to explode via hydrodynamics rather than by delayed neutrino heating [471] as in the NDW *r* process. This avoids some of the issues with neutrino interactions in the NDW models. In this scenario the prompt shock itself is sufficiently robust as it bursts through the outer layers of the proto-neutron star to directly eject neutronized matter which subsequently experiences an *r* process.

6.4. Neutron star mergers

In recent years by far the most popular model [e.g. 401] for *r*-process nucleosynthesis is based upon binary neutron-star mergers. This scenario can involve either two neutron-stars ($NS + NS$) or a neutron-star plus black-hole ($NS + BH$) binary [e.g. 74,77,401,411,412,428,497–502].

Indeed, since the observation [14,391–397] of the gravitational waves emanating from GW170817 and the associated kilonova and GRB from GW170817 there has been a flurry of models [15,439,503,504] describing the *r* process in NSMs and the associated hydrodynamic ejection of *r*-process material into the interstellar medium [505–508].

Ejected matter from NSMs can be very neutron-rich ($\langle Z/A \rangle \equiv Y_e \sim 0.1$). Hence, the *r*-process path can proceed along the neutron drip line all the way to the region of fissile nuclei ($A \approx 300$). Indeed, in such models, fission recycling can occur. That is, after the *r* process terminates by beta-induced or neutron-induced fission, the fission fragments each continue to experience neutron captures until fission again terminates the *r*-process path and the process repeats. In this process the abundances can become dominated by the fission fragment distributions after a few cycles. Hence, the β-decay flow near the neutron closed shells is not as important. In that sense, the nuclear physics for NSMs is quite robust [509]. However, this paradigm is very sensitive to theoretical models of extrapolated nuclear properties near the termination of the *r* process, particularly fission barriers and fission mass distributions [11].

A number of studies [74,77,407,408,428,498,499] have indicated that the *r* process in NSMs can produce a final abundance pattern that is similar to the solar *r*-process abundances, but only for heavier A> 130 nuclei. However, the distribution of nuclear fission products strongly affects the final abundance pattern [510]. Extrapolation of fission fragment distributions (FFDs) to the vicinity of the *r*-process path [e.g. 510–512], however, is fraught with uncertainty. It has been suggested [11], for example, that incorporating a model that leads to a broad distribution of fission fragments, smooths out the effect of the neutron closed shells, thereby providing a means to fill in the isotopes bypassed in the main *r* process.

Current microscopic calculations [e.g. 511] tend to produce lower fission barriers and narrower fragment distributions as discussed below. However, the *r*-process study of Shibagaki et al. [11] made use of β-decay rates, β-delayed neutron emission probabilities, and β-delayed fission probabilities taken from [24] based upon fits to known fragment distributions. The spontaneous fission rates and the α-decay rates were taken from Koura [513]. For these rates β-delayed fission is the dominant nuclear fission mode near the termination of the *r* process [514]. However, this is a phenomenological model.

From the perspective of galactic chemical evolution, it may be difficult for NSMs to reproduce the observed *r*-process abundance distribution of metal-poor stars at [Fe/H]< -3. A possible explanation is that the time scale of metal enrichment in the most metal-poor stars does not follow a simple age-metallicity relation as a simple one-zone model for the halo. That is, some of the enrichment of *r* elements may occur in dwarf galaxies or the IGM that later are incorporated into the Galactic halo. This explanation has been corroborated by kinematic studies [515] of the Galactic halo indicating that the *r*-enhanced stars are the result of late mergers.

For example, Hirai et al. [516] considered the chemical evolution in dwarf spheroidal galaxies (dSphs). Such dSphs are the building blocks of the Galactic halo and have a much lower star formation efficiency than that of the Milky way halo. That paper showed that when the effect of metal mixing was taken into account, the enrichment of *r*-process elements in dSphs by NSMs could reproduce the observed [Eu/Fe] vs. metallicity distribution with a merger delay time of as much as 300 Myr. This is because metallicity is not really correlated with the time $\sim$300 Myr from the start of the simulation due to the low star formation efficiency in dSphs. They also confirmed that this model is consistent with observed properties of dSphs such as the radial profiles and metallicity distribution. A merger time of $\sim$300 Myr and a Galactic NSM rate of $\sim 10^{-4}$ yr^{-1} could reproduce the abundances of metal poor *r*-process enhanced stars and is consistent with the values suggested by population synthesis and other nucleosynthesis studies.

Similarly, Komiya and Shugiyama [517] re-examined the enrichment of *r*-process elements by NSMs considering this difference in propagation using a chemical evolution model based upon hierarchical galaxy formation. They found that observed *r*-process enhanced stars around [Fe/H]-3 are reproduced if the star formation efficiency is lower for low-mass galaxies using a realistic delay-time distribution for NSMs. They showed that a significant fraction of NSM ejecta escape from its host proto-galaxy and pollute intergalactic matter as well as other proto-galaxies. The propagation of *r*-process elements over proto-galaxies was shown to reduce the abundance distribution at [Fe/H]< -3. They could obtain a distribution compatible with observations of the Milky Way halo stars. In particular, the pre-enrichment of the intergalactic medium explains the observed scarcity of extremely metal-poor stars without Ba and the abundance distribution of *r*-process elements at [Fe/H]≤ -3.5. However, these considerations suggest that the evolution at low-metallicity may not be in contradiction to a NSM origin; also at high metallicity the presumably-dominating Fe contributions from SN Ia affect the Eu/Fe correlation and are a concern.

6.5. Black hole-neutron star mergers

During the merger of a black hole and a neutron star, baryonic mass can become unbound from the system. Because the ejected material is extremely neutron-rich, the *r* process rapidly synthesizes heavy nuclides as the material expands and cools [499,502,518–520].

In Roberts et al. [520], models of black hole-neutron star mergers were mapped into a Newtonian smoothed particle hydrodynamics (SPH) code and the evolution outflows were followed. It was found that the ejected material produces *r*-process nucleosynthesis even for unrealistically high neutrino luminosities, due to the rapid velocities of the outflow. Neutrinos could, however, have an impact on the detailed pattern of the *r*-process nucleosynthesis.

In Fernández et al. [519] an investigation was made into the ejecta from black hole–neutron star mergers by modeling the formation and interaction of mass ejected in both the tidal tail and a disk wind. The nucleosynthetic yields in the outflows were obtained using a post-processing nuclear reaction network. The kilonova emission was also computed with a radiative transfer code. A large initial tail mass resulted in the fall-back of matter into the disk that was then ejected in a disk wind. Relative to the case of a disk without dynamical ejecta, the combined outflow had lower mean electron fraction, faster speed, larger total mass, and larger absolute mass free of high-opacity lanthanides or actinides. They found that in most cases, the nucleosynthetic yield was dominated by the heavy *r*-process contribution from the unbound part of the dynamical ejecta. A solar-like abundance distribution could be obtained when the total mass of the dynamical ejecta was comparable to the mass of the disk outflows.

In Kyutoku et al. [502] a fully general-relativistic neutrino-radiation-hydrodynamics simulation was made of the merger of black hole-neutron star binaries throughout the coalescence. This work particularly focused on the role of neutrino irradiation in dynamical mass ejection. This study confirms that the ejecta from black hole-neutron star binaries are indeed very neutron rich and should accommodate a strong *r* process unless magnetic or viscous processes contribute substantially to the mass ejection from the disk.

In Wu et al. [521] *r*-process nucleosynthesis in outflows from black hole accretion disks formed in double neutron star and neutron star-black hole mergers was studied. They found that these outflows, powered by angular momentum transport processes and nuclear recombination, can be a dominant source for the total mass ejected by the merger. They calculated the nucleosynthesis yields from the disk outflow using thermodynamic trajectories from hydrodynamic simulations. It was found that outflows can produce a robust abundance pattern around the second *r*-process peak (mass number A $\sim$ 130), independent of model parameters, with significant production of A $<$ 130 nuclei. This suggests that dynamical tidal ejecta with a high electron fraction may not be required. Disk outflows reached the third *r*-process peak (A $\sim$ 195) in most simulations, although the amounts depended strongly on the model parameters.

6.6. Magneto-hydrodynamic jet models

The magneto-hydrodynamic jet (MHDJ) supernova model [522–524] remains as a viable alternative. In this scenario magnetic turbulence leads the launch of neutron rich material into a jet. As this material in the jet is transported away from the neutron star it can undergo *r*-process nucleosynthesis. Since material is transported away quickly it avoids the problems associated with neutrino interactions near the proto-neutron star as in the NDW model. Moreover, the required timescale, neutron density, temperature, entropy, electron fraction are easily achieved in this model. Such jet models also can naturally provide a site for a strong but rare *r* process early in the early history of the Galaxy as required from astronomical observations [400].

The MHDJ supernova model is described in detail in Nishimura et al. [522] and Winteler et al. [523]. In Nishimura et al. [522], two-dimensional MHD simulations were carried out from the onset of the core collapse through the shock propagation into the silicon-rich outer layers ($\sim$500 ms after bounce). The *r*-process nucleosynthesis was calculated in the later phase by employing two different paradigms for the extrapolations of temperature and density in time starting from the composition produced the explosion.

It was found [522] that a jet-like explosion could be formed from the combined effects of rapid rotation and a strong initial magnetic field. A ratio of rotational energy to gravitational energy $T/W \approx 0.5\%$ was adapted along with a magnetic field of $\sim 10^{13}$ G. As the ejected low Y_e material in the jet emerged from the silicon layers, an *r* process occurred that reasonably reproduced the solar *r*-process abundance distribution up to the third ($A \approx 195$) peak.

In Winteler et al. [523] the MHDJ simulations were elaborated by utilizing a three-dimensional magneto-hydrodynamic core-collapse supernova model and also including an approximate treatment of the neutrino transport. Similar to the two-dimensional calculations, bipolar jet formation required a rare progenitor configuration involving a high rotation rate ($T/W \approx 0.8\%$) and a large magnetic field (5×10^{12} G). The conservation of magnetic flux amplified the initial magnetic field to $\sim 10^{15}$ G during collapse. Similar to the models of Nishimura et al. [522], the low Y_e material ejected with the jet experienced *r*-process nucleosynthesis that reproduces the solar *r*-process element distribution. However, many of the jet simulations tend to under-produce nuclides just below and above the *r*-process abundance peaks. This tendency seems to be a generic weakness of the MHDJ model.

6.7. *I*-process

In Hempel et al. [525] a study was made of an intermediate *r* process (*I*-process) motivated by observed carbon-enhanced metal-poor (CEMP) stars in the Galactic Halo. These stars display enrichments in heavy elements associated with either the s or the r neutron-capture process (e.g., barium and europium, respectively), and in some cases they display evidence of both. The abundance patterns of these CEMP-s/r stars, are particularly puzzling, since the *s* and the *r* processes are thought to occur in very different astrophysical conditions. They investigated whether the abundance patterns of CEMP-s/r stars can arise from the nucleosynthesis of the *I* process, which is characterized by neutron densities intermediate between those of the *s* and the *r* processes. They considered different constant neutron densities ranging from 10^7 to 10^{15} cm^{-3}. They showed that the *I*-process models successfully reproduced the observed abundance patterns of 20 CEMP-s/r stars.

Rapidly-accreting white dwarfs [526] and low Z AGB stars [527] were proposed as possible sites. In an attempt to explore an intermediate process from the sources of the *r* process, Nishimura et al. [518] investigated *r*-process nucleosynthesis in magneto-rotational supernovae, based on an explosion induced by the magneto-rotational instability (MRI). A series of axisymmetric magnetohydrodynamical simulations were performed that numerically resolved the MRI. Neutrino-heating dominated the explosions and enhanced by magnetic fields, showed mildly neutron rich ejecta producing nuclei up to A $\sim$ 130 (i.e., the weak *r* process), while explosion models with stronger magnetic fields reproduced a solar-like *r* process. However, the most common abundance patterns in their models were between the weak and regular *r* process. These models produced light and intermediate mass nuclei. A variety of abundance distributions were identified. Some of these were consistent with *I*-process abundance patterns in *r*-process enhanced metal-poor stars. These models indicated that magneto-rotational supernovae may also provide the desired environment for *I*-process nucleosynthesis.

6.8. Collapsar *r* process

There has been some interest [528–534] in the possibility of *r*-process nucleosynthesis in the relativistic jets associated with the collapsar (failed supernova) model for gamma-ray bursts. (See Nakamura et al. [533] and Nakamura et al. [534] for reviews.)

Collapsars [535–541] are a favored model for the formation of observed long-duration gamma-ray bursts (GRBs). In the collapsar paradigm the central core of a massive star collapses to a black hole. However, the angular momentum of the progenitor star leads to the formation of a heated accretion disk around the nascent black hole. Material is material from a polar funnel region by magnetic field amplification and heating from the pair annihilation of thermally generated neutrinos emanating from this accretion disk. This then leads to an outflow of neutron-rich matter from the accretion disk into a relativistic jet along the polar axis.

A large volume of work has explored the formation of such collapsars [e.g. 542–547, and references therein] and the development of the associated relativistic jets [e.g. 528,537–541,548–555].

The axi-symmetric special relativistic magneto-hydrodynamics (MHD) *r*-process study of Nakamura et al. [534] made use of a model from Harikae et al. [556] for slowly rotating collapsar models. A method developed in Harikae et al. [557] was applied to compute the detailed neutrino-pair heating by ray-tracing neutrino transport. Hydrodynamic studies of material in the heated jet along with the associated nucleosynthesis were evolved out to the much later times and lower temperatures associated with the *r* process. In particular, that paper explored whether the highly relativistic jet heated via neutrino-pair annihilation of the collapsar model is capable of generating the high entropy per baryon and neutron-rich material required for an *r* process.

It was found [534] that this environment could indeed produce an *r*-process-like abundance distribution. However, the very rapid time scale and high entropy caused the abundances to differ from the solar abundance distribution. This is an extreme example of a model with a very rapid freezeout that underproduces isotopic abundances above and below the main *r*-process peaks.

There is a persistent problem in the MHDJ model, or any model [e.g. 489] in which the *r*-process elements are produced on a short time scale via the rapid expansion of material away from the neutron star. Most such models under-produce isotopic abundances just below and above the *r*-process abundance peaks.

This can be related to the conditions of freezeout when the neutrons are exhausted and the synthesized nuclides begin to β decay back to the region of stable isotopes. Neutron captures and photo-neutron emission proceed in equilibrium for nuclei with a neutron binding energy of about 1–2 MeV. For *r*-process models with a rapid transport time, the density diminishes rapidly so that a sudden freezeout occurs close to the *r*-process path. As this occurs there is a region along the *r*-process path above and below closed neutron shells where the *r*-process path shifts abruptly toward the closed shell from below (or away from the closed shell for higher nuclear masses). This shifting of the *r*-process path causes isotopes with N = 70–80 (A $\sim$110–120) or N =90–100 (A $\sim$140–150) to be bypassed in the β-decay flow. Indeed, this was a consistent feature even in the original realistic NDW models of Woosley et al. [12]. Indeed, this effect has been apparent in most *r*-process calculations since the 1970s [e.g. 405].

6.9. *r*-process from dark matter induced black hole collapse

In Bramante and Linden [558] it was suggested that a new paradigm may occur as an explanation of the high *r*-process abundances in the Reticulum-*II* dwarf galaxy. They argue that the binary NSM scenario is extremely unlikely, because binary stellar evolution models require a significant supernova kick to produce NS–NS or NS-black hole (BH) merger [559,560]. However such kicks would remove the compact binary system from the weak gravitational potentials of the ultra-faint dwarf spheroidal. They considered a novel mechanism whereby neutron stars in regions of high dark-matter density implode after accumulating a enough mass of DM. They found that *r*-process proto-material is ejected by the tidal forces when a single NS implodes into a BH. The rate also matches that required for the *r*-process abundance of both Reticulum II and the Milky Way. They also noted that such DM models which collapse a single NS may also solve the missing pulsar problem in the Milky Way Galactic Center.

6.10. The *tr*-process

The abundance patterns for some observed stars do not fit the standard *r* process. In Boyd et al. [561] and Famiano et al. [562] it was hypothesized that such abundance patterns might be produced by failed supernovae. In particular they considered stars for which their core at first collapses to form a neutron star. However, subsequent infall onto the proto-neutron star causes it to collapse to a black hole. This is the so-called *fall-back supernova*.

Stars in this class span a mass range from roughly 25 to 40 solar masses [563] for low-metallicity stars. When the neutron star collapses to a black hole the ongoing *r*-process ceases, terminating either when the *r*-processed regions are swallowed by the black hole or when the electron anti-neutrinos fall below the event horizon. Thus, this truncated *r* process, or *tr* process, nucleosynthesis could terminate a neutrino-driven wind *r* process. This scenario, however depends upon the precise time at which the black hole prevents further *r*-process production or the emission of nuclides into the interstellar medium. The delayed collapse to a black hole, combined with the difficulties in observing the higher mass rare-earth elements, could suggest a cutoff in the *r*-process distributions at around $A \approx 165$. To implement this scenario, the authors simply assumed that mass layers that produce the lighter *r*-process nuclei are ejected prior to those that produce the heavier *r*-process nuclides.

As a possible additional benefit of the *tr*-process, it was noted in Boyd et al. [561] that in some cases the stars produced no nuclides in the $A = 130$ peak or beyond. This could have the effect of enhancing the yields of the lightest *r*-process nuclides relative to the main *r* process. Hence, this could provide an alternative means to fill in nuclei in the $A = 110$–120 region. Indeed, evidence in metal poor stars of the production of nuclides in the $A = 110$–120 mass region and lighter may indicate a *tr*-process origin. This conclusion, however, is very dependent upon nuclear properties of the light neutron-rich nuclei along the *r*-process path and requires a much more detailed simulation of the relevant astrophysics. In Famiano et al. [562] it was shown that the scatter of [Sr/Ba] in metal-poor stars is very sensitive to the adopted equation of state, and hence, might be used as a diagnostic.

7. Summary and prospects

In summary, we are at a very unique time in history with regard to unraveling the mystery of *r*-process nucleosynthesis. For the first time Nature has revealed *r*-process nucleosynthesis in real time in the form of a binary neutron star merger and the associated kilonova.

For the first time we have opportunities to directly and indirectly probe properties of nuclei far from stability with the advent of radioactive ion beam accelerators already in existence and soon to come online. This forefront is accompanied with astronomical observations of metal poor stars in the halo of our Galaxy and in dwarf galaxies in the Local Group. These have revealed the complex dynamics of mergers and nucleosynthesis and the existence or rare *r*-process events that eject large amounts of *r*-process material in the poorly mixed interstellar medium of dwarf galaxies.

Nevertheless, uncertainties and mysteries remain. Just to name a few: Is the *r*-process abundance distribution in the solar system the result of one or multiple environments? What are the roles of fission fragment yields and neutron-induced or β-induced fission on the termination of the *r* process, and what are the associated fission fragment mass distributions? Is there fission recycling in the *r* process? What are the actinide-boost stars? Do they indicate the existence of fission recycling? What are the roles of individual nuclei and their neutron-capture and β-decay rates in determining the final *r*-process abundances? Does a more accurate description of the neutrino transport, including oscillations and other quantum effects significantly change the predicted *r*-process yields?

In conclusion, although great progress has been made and is being made, there is still much work to be done to unravel the mystery of *r*-process nucleosynthesis in the Galaxy. Even so, with the current advance of astronomical instrumentation, nuclear measurements, and nuclear theory, a definitive understanding of the *r* process is within reach.

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