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Opportunities for nuclear astrophysics at FAIR

K. Langanke^{1,2}

¹GSI Helmholtzzentrum für Schwerionenforschung, Planckstr. 1, 64291 Darmstadt, Germany

²Institut für Kernphysik, TU Darmstadt, Schlossgartenstr. 9, 64291 Darmstadt, Germany

E-mail: k.langanke@gsi.de

Abstract. The Facility for Antiproton and Ion Research FAIR is a new accelerator complex currently under construction in Darmstadt, Germany. FAIR will offer unprecedented research opportunities in nuclear, hadron and atomic physics and in several applied sciences. This manuscript discusses how FAIR will advance our understanding of the origin of the elements in the universe and of the astrophysical objects which produce them.

1. Introduction

Our understanding of the origin of the elements in the universe [1] and of the astrophysical objects which produce them has significantly advanced since Radioactive Ion-Beam (RIB) facilities allow to produce and study the short-lived nuclei which play often crucial roles in these astrophysical scenarios. A further advance is expected from FAIR, with its unique combination of high-intensity, high-energy accelerators for all ion species (and antiprotons), high- and low-energy storage rings, a superconducting Fragment Separator and a large variety of fore-front detector systems. In particular the use of the storage rings will allow precision measurements of masses, half-lives and reaction cross sections of many short-lived nuclei which until now have not been experimentally accessible. Furthermore the high-intensity beams will be exploited in relativistic heavy-ion collisions which will shed light on the nuclear Equation of State (EoS) and will progress our knowledge about the properties of matter inside neutron stars.

There has been significant advances in the understanding of explosive astrophysical objects due to progress in nuclear (and astrophysical) modelling and due to some key measurements performed at existing RIB facilities or in selected stable-beam experiments [2, 3, 4]. In this manuscript we will briefly review two recent developments: the improved description of nuclear physics input in supernova simulations and the discussion of neutron-star mergers as a potential production site of heavy elements in the Universe via the astrophysical r-process. Despite the important progress achieved in the combined efforts of experimental and theoretical nuclear physics and of astrophysical modelling and astronomical observation many open questions, however, still remain which hopefully can be addressed once next-generation facilities like FAIR are operational.

2. FAIR and supernovae

A massive star ends its life in a supernova explosion triggered by the gravitational collapse of its inner core. The collapse comes to a halt when the inner region of the core has reached nuclear matter densities. A shock wave is created which, with the help of energy transport by neutrinos



and by convective motion, ejects the outer shells of the star [5, 6]. Nuclear physics plays an important role at various stages of the explosion and FAIR can contribute to all of them, as we briefly discuss in the following.

2.1. Electron capture during collapse

Electron captures onto nuclei play crucial roles for the dynamics of the collapse [7, 8]. These captures are made possible as the Fermi energy ϵ_F of the relativistic electron gas exceeds typical nuclear Q -values at densities of 10^9 g/cm³ and beyond. Continuous electron captures reduce the pressure which the degenerate electron gas can exert against the collapse and cools the core due to the emission of neutrinos associated with the captures. Finally the electron capture drives the matter composition in the core, which is in nuclear statistical equilibrium, to heavier and more neutron-rich nuclei. Due to the effective cooling, the entropy in the core stays low and heavy nuclei survive the collapse [7].

During the early collapse, where the core composition is dominated by nuclei from the iron-nickel mass range (pf shell nuclei), the capture process is dominated by Gamow-Teller (GT) transitions. As under these conditions $\epsilon_F \sim Q$, the capture rates are quite sensitive to a detailed and accurate description of the GT distribution. The pioneering work to measure GT strength functions has been performed at TRIUMF using (n,p) reactions, achieving, however, only modest energy resolutions [9]. This situation has been dramatically improved by the development of the (d,²He) technique at the KVI Groningen which allowed to determine GT distributions for many nuclei in the iron-nickel mass range with an energy resolution of about 150 keV [10]. Furthermore, modern diagonalization shell model calculations have been proven to reproduce the measured distributions quite well [11] and are hence the method of choice to calculate the relevant stellar electron capture rates for the early collapse phase [12, 13]. In a detailed comparison to experiment Cole *et al* [14] confirmed that the diagonalization shell model indeed gives a reliable description of early stellar electron capture. We note that in the stellar environment electron capture is reduced (approximately by a factor of order 2) due to screening effects [15]. As beta decays are enhanced by screening, stellar environment effects can alter the conditions at which URCA pairs operate [43]. This is particularly important for the core collapse of $8 - 12M_\odot$ stars, (electron capture supernovae) [17], where several URCA pairs influence the dynamics of the core evolution.

In the later stage of the collapse of massive stars, the nuclei present in the core composition get heavier and more neutron-rich. At these conditions the electron Fermi energy is noticeably larger than the nuclear Q values and the electron capture rates are mainly sensitive to the total GT strength and its centroid. These quantities are well described by an hybrid approach proposed in [18]. The calculations are then based on a statistical shell model approach (Shell Model Monte Carlo (SMMC) [19]) which allows to determine nuclear properties at finite temperature and in large multi-shell model spaces taking the relevant nuclear correlations into account. Such correlations are particularly important for nuclei with proton number below and neutron number above an oscillator shell closure (like $N=40$). In such situations GT transitions would be completely blocked by the Pauli principle in the Independent Particle Model (IPM) [20] suppressing electron capture on nuclei drastically. However, it has been shown in [18] that nuclear correlations induced by the residual interaction move nucleons across the shell gap enabling GT transitions and making electron capture on nuclei the dominating weak interaction process during collapse [18, 21]. This unblocking of the GT strength across the $N = 40$ shell closure has been experimentally confirmed for ⁷⁶Se (with 34 protons and 42 neutrons) [22], in agreement with shell model studies [23]. Furthermore, shell model studies clearly show that the description of cross-shell correlations is a rather slowly converging process requiring the consideration of multi particle-multi hole configurations [24, 25, 26, 23].

As most of the relevant neutron-rich nuclei, encountered in the later stage of the collapse,

are unstable, the measurement of the respective GT distributions requires charge-exchange experiments in inverse kinematics. Due to the mass difference between the (unstable) heavy projectile and the lighter target such experiments are only possible at RIB facilities with high-energy secondary beams. In a landmark experiment the GT strength has been measured for the unstable nucleus ^{56}Ni [27]. At FAIR the EXL collaboration will perform such experiments in storage rings with stored and cooled ions which increases the effectiveness drastically. FAIR will decisively contribute to the fundamental issue of cross-shell correlations by spectroscopy and reaction experiments with neutron-rich nuclei, in this way deepening our understanding of GT unquenching and guiding improved models.

The shell model weak-interaction rates have significant impact on collapse simulations. In the presupernova phase ($\rho < 10^{10} \text{ g/cm}^3$) the captures proceed slower than assumed before and for a short period during silicon burning β -decays can compete [28, 29]. As a consequence, the core is cooler, more massive and less neutron rich before the final collapse. Based on the SMMC calculations it has been shown in [18] that capture on nuclei dominates over capture on free protons. Also changes of the supernova trajectories compared to previous simulations with less accurate capture rates are significant [6, 18, 30].

The shell model electron capture rates [12, 13], which are noticeably slower than the pioneering rates of Fuller *et al.* (FFN) for pf shell nuclei [31], have also important consequences in nucleosynthesis studies for thermonuclear (type Ia) supernovae by yielding larger electron-to-nucleon ratio behind the burning front than obtained with the FFN rates [32].

2.2. Shock wave and Nuclear Equation of State

When the interior of the collapsing core reaches nuclear matter densities (or slightly beyond), a shock wave is created at the surface of the so-called homologous core of about $0.5 M_{\odot}$. The shock loses energy by dissociation of nuclei into free nucleons so that its energy is insufficient to traverse the infalling matter of the iron core. The shock gets stalled and becomes revived by energy transport due to neutrinos from the hot interior and to convective motion. Details of this picture depend strongly on the nuclear Equation of State (EoS) which is subject of intensive experimental studies at FAIR exploiting relativistic collisions in which a high-intensity, high-energy beam of heavy ions is impinged on a fixed target and creates, for a short time, a hot fireball of nuclear matter, where energy is transferred into the generation of pairs of short-lived particles. Due to their relatively long mean free paths, di-lepton pairs are well-suited probes to study the properties of the fireball matter. This is achieved by the FAIR detectors HADES and CBM, where CBM due to its unprecedented event rate capabilities will also observe rare probes like particles with charm quarks created in the fireball [33]. Recent supernova simulations [34], which also considered muons as substitute of high-energy electrons in the EoS, indicate that the density/temperature regime reached in the collapse correspond very well to the parameter space which is exploited by the HADES experiment [35].

Two properties of the EoS are subject of other experimental approaches at FAIR. The compression modulus can be studied by excitation of the giant monopole resonance, which is planned as an experimental storage ring program by the EXL collaboration. Using inverse kinematics, such experiments can be performed for different (stable and unstable) nuclei within a long isotope chain to explore additionally the isospin dependence of this quantity. The isospin dependence enters also via the symmetry energy into the EoS. It has been shown that the symmetry energy scales with the dipole polarizability [36] and the difference between nuclear mass and charge radii [37]. An intensive program to study these quantities is envisioned by the $R^3\text{B}$ collaboration at FAIR by means of Coulomb excitation.

2.3. Explosive and neutrino nucleosynthesis

During the explosion matter is ejected from the surface of the nascent neutron star, triggered by neutrino interactions. Due to the high temperatures involved, the matter exists originally as free nucleons, which upon reaching cooler regions can combine to nuclei. The abundances produced in this 'neutrino-driven wind' nucleosynthesis depends crucially on the proton-to-neutron ratio of the ejected matter which is determined by the competition of neutrino and antineutrino absorptions on neutrons and protons, respectively, and depends strongly on the neutrino luminosities and spectra [38]. Simulations show that the proton-to-neutron ratio can vary with time so that the ejected matter can be either proton rich (leading to νp -process nucleosynthesis [39, 40, 41]) or slightly neutron rich (resulting in a weak r-process which can produce nuclides up to mass number $A \sim 130$, but not the elements in the third r-process peak ($A \sim 195$) [43, 44]). Finally, when the neutrinos pass through the outer stellar shells they can contribute to the production of selective nuclides by neutrino-induced spallation reactions on more abundant nuclei [42]. Calculations show that this neutrino-nucleosynthesis process is important for production of ^{11}B , ^{19}F , ^{138}La and ^{180}Ta [45], but also for isotopes ^{22}Na and ^{26}Al [46], which both play an important role in radioastronomy.

3. Neutron-star mergers as a site for the r-process

The r-process is the astrophysical origin of about half of the elements heavier than iron. It occurs in an astrophysical environment with extreme neutron densities [47]. As a consequence the r-process path in the nuclear chart runs through nuclei with such large neutron excesses that most of them have yet not been made in the laboratory and their properties have to be modelled. Of particular importance are the nuclei with magic neutron numbers. With their relatively long half-lives, as predicted by theory, they act as obstacles in the r-process flow (so-called waiting points).

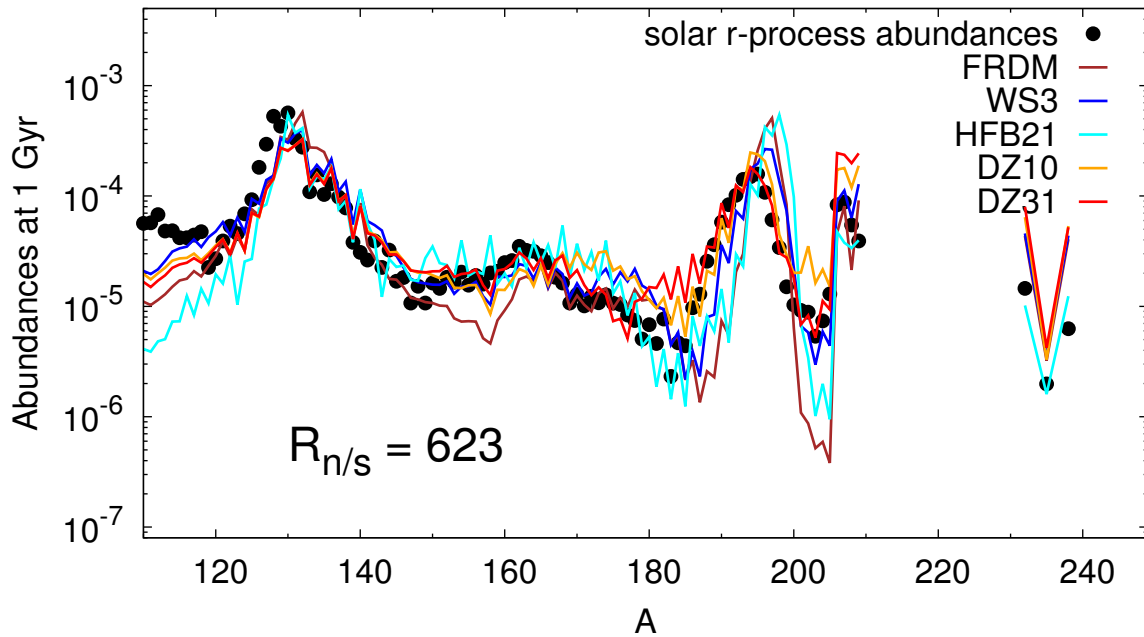


Figure 1. Final r-process abundances at a time of 1 Gyr for various mass models and a selected neutron-star merger trajectory with initial neutron-to-seed, $R_{n/s} = 623$. The peaks at around $A = 130$ and 195 are referred to as second and third r-process peaks. (from [53])

The astrophysical site of the r-process is still an open question. Recent observations of the abundances of r-process elements in old metal-poor stars might even point to (at least) two different sites: the abundances of the elements with mass numbers $A > 130$ show the same relative pattern as found in the solar system (i.e. accumulated over the history of the galaxy until the solar system was formed), while the abundances of the lighter elements in these stars are underproduced relative to solar (e.g. [48]). Neutron-star mergers are discussed as the site for the robust production of the heavy r-process nuclides (with $A > 130$) [49, 50], while the neutrino-driven wind from the nascent neutron star in a core-collapse supernova might contribute additionally to the production of the lighter nuclides [43, 44].

R-process simulations in a neutron-star merger environment show several noticeable features. At first, the matter ejected during the merger expands and cools and by beta-decay of very neutron-rich nuclei is reheated to establish an $(n, \gamma) \rightleftharpoons (\gamma, n)$ equilibrium [51]. Another characteristic of r-process simulations for neutron star mergers is the occurrence of fission cycling. Here the very extreme neutron densities support mass flow up to the mass range $A \sim 280 - 300$ where the nuclei decay by fission, producing nuclides around ^{132}Sn as fission fragments. Simulations thus have the interesting feature that the third peak is generated by neutron captures already before freeze-out, while the second peak at $A \sim 130$ and the lead peak develop as products of fission and alpha decays, respectively, at late stages of the process after freeze out. In fact, using neutron-star trajectories from Ref. [52], Ref. [53] succeeded to achieve a rather robust r-process pattern between the second and third peaks in close resemblance with the solar r-process distribution (see Fig. 1).

It is intriguing to speculate that neutron star mergers might be responsible for the robust r-process patterns observed in old metal-poor stars [48]. This requires, however, that the frequency of neutron star mergers is sufficiently large during the early time of our galaxy which is yet an open question. A proof that neutron-star mergers are indeed sites of r-process nucleosynthesis might come from the direct observation of the associated electromagnetic transient, called kilonova [54]. The respective lightcurve is produced by the radioactive decay of freshly synthesized nuclei, in particular, by alpha decays of actinides. Hence the lightcurves are very sensitive to the amount of actinides produced in the r-process which in turn depends on the mass flow through the third r-process peak.

Despite these intriguing results, the simulation of Ref. [53] shows a sensitivity to the properties of nuclei around the third r-process peak. These nuclei are the domain of FAIR, which with its high-energy primary beams, isotopic-pure secondary beams and storage rings offer unique opportunities to produce and study, for the first time, the masses, half-lives and beta-delayed neutron emission probabilities of the nuclei in the $A \sim 195$ r-process peak. In particular, these measurements will test the recent predictions [55, 56] that forbidden transitions contribute significantly to the half-lives of the $N = 126$ r-process nuclei resulting in a faster mass flow through the third r-process peak.

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