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ACCRETING NEUTRON STARS AND RADIOACTIVE BEAM EXPERIMENTS*

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The nuclear processes on accreting neutron stars in X-ray binaries are related to a number of open astrophysical questions. I review these open questions, their relation to the α p, rp and crust processes, and the nuclear data needed to solve the problems. Data on very unstable proton and neutron rich nuclei are most critical, and therefore radioactive beam experiments together with progress in the theoretical understanding of nuclei far from stability are needed.

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1. Introduction

Recent progress in astronomy had a strong impact on nuclear astrophysics. New observations shed new light on some of the longstanding problems, but also expanded the scope of the field considerably beyond the traditional questions of the origin of the elements and energy generation in stars. Among the most interesting of these new observations is the detection of a multitude of oscillation phenomena in the X-ray flux from accreting neutron stars (X-ray binaries). These observations might shed light on the properties of neutron stars in an unique environment and might, therefore, lead to new insights about the properties of matter under extreme densities.

However, interpretation of the new observational data and finding answers to the open questions requires similar advances in our understanding of the underlying nuclear physics. In this paper I review some of the open questions concerning X-ray binaries, their relation to nuclear physics, the nuclear data needed to find the answers, and the future developments in experimental and theoretical nuclear physics needed to obtain these data.

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In an X-ray binary system a neutron star (or in some cases a black hole) orbits a regular companion star (see the reviews [1–3]). The two stars are so close that mass flows from the envelope of the companion star onto the surface of the neutron star. The energy that gives rise to the observed, bright X-ray radiation is generated in two ways: (1) The gravitational energy released during the infall of the accreted matter onto the neutron star surface gives rise to a bright, persistent X-ray flux that is correlated with the global accretion rate. (2) The strong gravity on the neutron star surface compresses and heats the accreted matter and as a consequence thermonuclear reactions set in and fuse hydrogen and helium into heavier elements. The energy per accreted nucleon generated by the thermonuclear processes is about a factor of 40 smaller than the gravitational energy. Nevertheless, if the thermonuclear burning is unstable the thermonuclear energy is released within a very short time and can be observed directly as type I X-ray bursts. Such bursts occur for accretion rates roughly below the Eddington limit [4–6] (which is the accretion rate where the radiation pressure from the gravitational energy release balances gravity). At such lower accretion rates temperatures in the accreted layer are initially not high enough to trigger helium burning via the $3\alpha \to ^{12}\mathrm{C}$ reaction. A hydrogen and helium rich layer can then accumulate on the neutron star surface for hours to days. During accretion nuclear reactions are confined to the β limited CNO cycles converting some of the accreted hydrogen into helium. Temperature and density at the bottom of the accreted layer rise slowly until eventually the onset of the 3α reaction triggers a thermonuclear runaway. In a thermonuclear runaway, an increase in temperature leads to a strong enhancement of the nuclear energy generation rate because of the temperature sensitivity of charged particle reaction rates. This in turn leads to a further rise in temperature. During the thermonuclear runaway, temperatures up to 2 GK are reached and hydrogen and helium are burned into heavier elements within 10–100 s. The heated layer emits bright X-ray radiation, which is observed as a type I X-ray burst (in contrast to type II bursts that are created by rapid changes in the accretion rate due to accretion disk instabilities). Once the burst is over, accretion of a fresh layer continues and after a few hours or days the next burst occurs.

2. Signatures of nuclear processes in X-ray binaries

It is likely that the strong gravity on the neutron star surface prevents ejection of the majority of freshly synthesized nuclei during an X-ray burst. So far, no direct observational information on the elemental composition of the ashes exist. Nevertheless, the nuclear processes on the surface and in the crust of the neutron star manifest themselves in a number of "indirect" observable signatures:

(1) Solar abundances: It has been proposed that small amounts of matter escaping into the interstellar medium during particularly violent X-ray bursts could be the origin of the light p-nuclei ^{92,94}Mo and ^{96,98}Ru in the solar system [7]. The origin of the unusually large abundances of these isotopes is a longstanding nucleosynthesis problem [8] (but see [9] for an alternative solution).

(2) Burst profiles: The energy release from the thermonuclear reactions during X-ray bursts is directly related to the observed rise and decay timescales of the X-ray bursts [10, 11]. These timescales show large variations between different sources, but also among bursts from the same source, ranging from 10 s to several minutes. A better understanding of the nuclear physics processes is needed to disentangle nuclear physics effects from other effects like burning front propagation across the neutron star surface, that can also affect burst timescales.

(3) X-ray flux oscillations: Nearly Coherent Oscillations (NCO's) with frequencies between 250 and 600 Hz have been discovered by the RXTE observatory in the X-ray flux from some type I X-ray bursts (see [12,13] for recent discussions). While NCO's most likely reflect the spin frequency of the burning surface layer, their behavior is strongly related to the nuclear processes during the burst. An expansion of the burning layer powered by nuclear energy could for example explain the 1–5 Hz drop observed in NCO frequencies during X-ray bursts. In this picture, the expanding burning layer decouples from the neutron star rotation and rotates slower during the burst due to angular momentum conservation. An improved understanding of the nuclear physics processes is needed to better understand these frequency changes and to relate them to the neutron stars gravity (and mass-radius relation) and surface properties in a quantitative way [14, 15].

(4) Secondary burning processes: A longstanding question concerning the final composition of the X-ray burst ashes is whether any potential fuel (hydrogen, helium, carbon) survives the burst and would be available for secondary burning processes in deeper layers. Many possible signatures have been associated with such secondary burning processes: thermonuclear reignition of unburned hydrogen could explain occasionally observed very short burst intervals [3]; electron capture on unburned hydrogen at greater depths could lead to very long bursts or flares ("deep hydrogen burning") [16]; more recently it has been suggested that relatively small amounts of carbon (of the order of 10%) in the X-ray burst ashes could ignite at greater depth and explain recently observed superbursts [17], bursts that are 1000 times more

energetic and 1000 times longer than ordinary type I X-ray bursts and have been observed occasionally in a number of sources. In connection with deep carbon burning it has been pointed out, that the ignition depth depends sensitively on the overall composition of the ashes (the average Z^2/A) because of its effect on the opacity. In fact, deep carbon flashes can only explain observed superbursts if one assumes ashes with heavy nuclei, for example a ^{104}Ru crust as predicted by recent rp-process (rapid proton capture process) calculations ([10] and see below). If this explanation is true then the mere existence of superbursts could be regarded as a signature of the heavy nuclei synthesized in the rp-process.

(5) Crust properties: The nuclei synthesized in thermonuclear reactions on the neutron star surface are buried by the continuously accreted matter and become part of the neutron star crust. The original catalyzed matter crust of the neutron star is replaced after the accretion of only about $10^{-4}M_\odot$ of material. Thus all neutron stars in low mass X-ray binaries (for example X-ray bursters) should have an accreted outer crust. The composition of the crust is determined by the thermonuclear processes on the neutron star surface as well as electron captures and pycnonuclear fusion reactions deeper in the crust. This composition determines the mechanical, thermal, and electrical properties which are related to a number of observational signatures. These include X-ray radiation observed from transient X-ray binaries during the off state when the accretion process shuts off [18–20]. This off state radiation has been interpreted as thermal radiation from the neutron star freshly heated during the preceding accretion phase. Such observations could lead to constraints on neutrino cooling, and therefore on the relevant pairing gaps for neutrons or, depending on the interior structure of the neutron star, for hyperons, or quarks [20]. As such crust effects should be absent in X-ray binaries that contain black holes, better criteria for the identification of black hole systems could also be derived [21]. However, this requires reliable models for the thermal structure of the crust, which depend critically on its composition and the location and rates of heat generating reactions and therefore on the underlying nuclear physics. This problem is also relevant for X-ray bursts as ignition conditions depend on the heat flux from the neutron star surface [14, 22].

Another long standing problem related to crust properties is the question of the evolution of magnetic fields. This is related to the fundamental question of why there are two classes of systems — bursters (with low magnetic fields; $\langle\approx 10^{12}$G) and pulsars (with high magnetic fields; $\rangle \approx 10^{12}$G).

Knowledge of the crust composition is a prerequisite for calculations of ohmic diffusion timescales, which play a critical role in all models that place the field generating currents in the neutron star crust (see [23] and references therein).

Crust properties could also by a key in understanding the surprisingly narrow spin frequencies range (250–600 Hz) of neutron stars in X-ray bursters inferred from NCO observations. A possible explanation for this puzzling observation is a balancing of the neutron star spin up from the accretion torque by gravitational wave emission [24] (but see [25] for another explanation of this observation based on a quark matter to normal matter phase transition in the center of the neutron star). One possible source of such gravitational wave emission would be a deformation of the crust induced by deep electron capture reactions resulting in a misaligned mass quadrupole moment of the neutron star. Accreting neutron stars are therefore promising targets for gravitational wave observatories like LIGO.

While (1)–(3) are observables only for X-ray bursters, (4)–(5) are observables for any accreting X-ray binary including X-ray pulsars, where high local accretion rates lead to continuous, stable burning of helium and hydrogen during the accretion process (steady state burning) [26, 27]. This typically happens in systems with strong magnetic fields ($>\approx 10^{12}$ G), where the accretion flow is funneled on a small surface area around the magnetic poles. The resulting hot spot rotates and gives rise to the observed pulsations.

In the following two sections I discuss first the thermonuclear reactions fusing hydrogen and helium into heavier elements within the accreted, surface layer, and then the reactions deeper in the crust of the neutron star.

2.1. Nuclear physics during thermonuclear burning

Fig. 1 shows the full sequence of nuclear reactions powering type I X-ray bursts calculated with a one zone model coupled self-consistently to a complete reaction network [10]. X-ray bursts are typically triggered by unstable helium ignition via the 3α-reaction, but it is the breakout of the CNO cycles into the αp-process and the subsequent hydrogen burning via the rapid proton capture process (rp-process) that is the major source of the burst energy. This has first been realized by Wallace and Woosley 1981 [28]. During ignition, the important nuclear physics parameters are the rates of the breakout reactions (see [29] for a recent review) $^{15}\mathrm{O}(\alpha,\gamma)^{19}\mathrm{Ne}$, and $^{18}\mathrm{Ne}(\alpha,p)^{21}\mathrm{Na}$ in connection with $^{14}\mathrm{O}(\alpha,p)^{17}\mathrm{F}$ as well as other reactions on small amounts of heavier seed nuclei present in the accreted matter. Bottlenecks for the latter processes are proton captures on $^{27}\mathrm{Si}$, $^{31}\mathrm{S}$, $^{35}\mathrm{Ar}$, and $^{39}\mathrm{Ca}$ [30]. These reactions determine the initial rise of the X-ray luminosity [31]. Following the breakout of the CNO cycle helium burns via the αp process, a sequence of

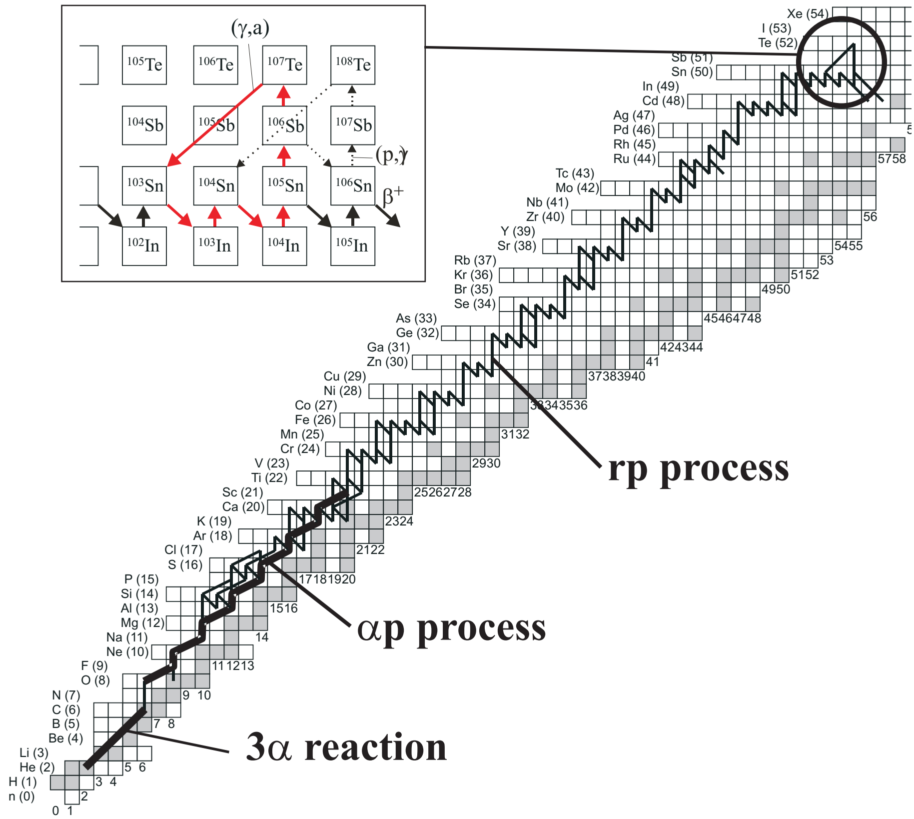

Fig. 1. Reaction flow time integrated over a complete X-ray burst. The inset shows the Sn–Sb–Te cycle in detail.

proton captures and (α, p) reactions at temperatures up to 2 GK. Hydrogen is needed as a catalyst for this process that ends at about $Z \approx 21$ because of the increasing Coulomb barrier for α induced reactions. In the αp process the competition of (α, p) reactions and (p, γ) reactions, especially at even–even $T_z = -1$ nuclei is critical, as the extent of the αp process determines the hydrogen to seed ratio for the rp-process [32].

The αp process provides seed nuclei for the hydrogen burning via the rapid proton capture process (rp-process). In the rp-process a sequence of proton captures ends at the proton drip line, when (γ, p) photodisintegration of a weakly proton bound isotone, or proton decay of a proton unbound isotone prevent further proton captures. The process then waits for the slower β^+ decay until it resumes proton captures back to the drip line. The rp-process reaches ^{56}Ni during the burst rise and continues during the cooling phase towards heavier elements.

The endpoint of the rp-process depends on the amount of hydrogen available at ignition, which is determined by the hydrogen contents of the accreted matter and the amount of hydrogen burning via the CNO cycles during the accretion phase that depends on the astrophysical parameters. The relation between the initial hydrogen abundance and the endpoint of the rp-process is not straight forward, as on one hand a larger hydrogen abundance can sustain a longer sequence of capture reactions but on the other hand the smaller amount of helium tends to decrease peak temperatures, which can lead to lighter seed nuclei and therefore reduces the hydrogen to seed ratio for the rp-process.

A longstanding problem in nuclear astrophysics was the question of the endpoint of the rp-process under favorable conditions (large amounts of hydrogen available). Earlier rp-process simulations for X-ray bursts were based on reaction networks that ended at Ni (for example [33]), in the Kr–Y region [11, 28, 34–36], and at Sn [7]. All these studies found that significant amounts of nuclei at the end of the respective networks were produced. This problem has finally been solved with the discovery of the Sn–Sb–Te cycle [10], that terminates the rp-process for initial hydrogen abundances of more than ≈0.4. Fig. 1 shows the reaction sequences in the cycle. The Sn–Sb–Te cycle occurs when the rp-process reaches the very α unbound, proton rich tellurium isotopes around ^{107}Te. These isotopes have substantial branchings for ground state α emission and at the high temperatures during the rp-process undergo rapid (γ,α) photodisintegration, which cycles the reaction flow back to Sn. The Sn–Sb–Te cycle(s) are an effective barrier for the rp-process under essentially all conditions. This includes steady state burning in accreting X-ray pulsars, where hydrogen is burned via the rp-process as well [10, 27]. For mass accretion rates in excess of about 10 times the Eddington limit the rp-process in X-ray pulsars is again limited by the Sn–Sb–Te cycle.

The Sn–Sb–Te cycle prevents the synthesis of nuclei more massive than $A \approx 106$ in the rp-process. This limitation could only be overcome in a multiburst rp-process where the freshly synthesized nuclei decay back to stability and are then again bombarded with protons in a second burst (the rp^2 process [37]). However, no realistic astrophysical scenario presently exists for such a repetitive multiburst rp-process.

The critical nuclear physics data for rp-process calculations are the nuclear masses around the proton drip line, β decay half-lives along the path (including decay from excited states), and proton capture rates within so called 2p capture sequences [7]. See the reviews [7, 38–40] for a more detailed discussion. A special role play the slowest β^+ decays along the reaction path (waiting points). Waiting points determine the final abundance pattern and the rp-process timescale. The latter is related to the observed burst timescale, hydrogen consumption, and the amount of ^{12}C in the ashes because ^{12}C production requires rapid depletion of hydrogen, which otherwise would destroy ^{12}C via proton captures.

2.1.1. Data needs for the rp-process — masses and half-lives

Over the last years radioactive beam experiments at a large number of different facilities have provided a wealth of new data on the location of the proton drip line between Ni and Te. These include experiments at LBL [41], GANIL [42–44], GSI [45–48], ISOLDE [49, 50], MSU/NSCL [51–53], and ORNL [54]. These experiments focused on the determination of the transition from β to proton decay as one moves away from stability, either by measuring β decay rates or by obtaining lifetime limits from the nonobservation of isotopes with known production rates. Proton emitters have in most cases been identified on the basis of such lifetime limits — with the exception of ^{105}Sb [41, 46] no direct proton emission has been observed in this element range. Owing to these experimental efforts and theoretical progress in mass predictions [40,55–57], the location of the proton drip line for odd Z elements is to a large extent established. This allows relatively reliable calculations of the location of the rp-process path and the identification of waiting points, which turn out to be the even–even $N = Z$ nuclei [7]. In fact, the interpretation of long X-ray burst tails as signatures of the rp-process [58] is largely based on the results of radioactive beam experiments at GANIL, ISOLDE, and MSU/NSCL. These experiments demonstrated that ^{69}Br and ^{73}Rb are proton unbound confirming that the relatively long-lived isotopes ^{68}Se and ^{72}Kr are indeed rp-process waiting points. Most of the relevant β decay rates along the rp-process path, with the exception of ^{74}Sr and ^{96}Cd, are experimentally known as well. The existence of the Sn–Sb–Te cycle also follows from experimental data, as the α separation energies of $^{106-110}$Te are accurately known from the detection of ground state α emission [59].

However, a major remaining uncertainty in rp-process calculations is the lack of sufficiently precise proton separation energies (accuracy $\approx kT =$ 80 keV needed) along the proton drip line between Ni and Te. Proton separation energies determine together with the β decay half-life the total lifetime of a waiting point nucleus in the rp-process (and whether a nucleus is a significant waiting point at all) [7]. As a consequence, uncertainties in nuclear masses can lead to order of magnitude uncertainties in the total lifetime of a waiting point [40]. This is a severe problem, as the dominant rp-process waiting points that determine the timescale for hydrogen burning are most likely some of the even–even $N = Z$ nuclei between Ni and Te. Similarly, uncertainties in the proton separation energies of Sb isotopes prevent a reliable calculation of the location of the Sn–Sb–Te cycle. This is critical, as for example lower proton binding energies of the Sb isotopes would move the cycle closer to stability thereby increasing the time it takes the rp-process to reach the cycle and reducing its importance for energy generation. The proton separation energy of ^{105}Sb is in principle known from the observation of proton emission. However, there is a discrepancy in the measured proton energy between the two different experiments [41, 46]. The proton separation energy of ^{106}Sb, is experimentally known as well. However, the mass of ^{106}Sb has been determined relative to the mass of ^{113}I via an observed α decay chain and a Q-value measurement of the β delayed proton emission of ^{114}Cs [45, 60]. Though this result is used in present rp-process calculations, there are potential systematic uncertainties and it and has not been adopted in the 1995 mass evaluation [61].

To summarize, the most critical data needed for rp-process calculations are nuclear masses along the proton drip line between Ni and Te. Especially important would be mass measurements of the even $N = Z$ nuclei, and for the proton rich Sb isotopes (which are on the neutron rich side of the $N = Z$ line) as in those cases masses cannot be determined from mirror nuclei and Coulomb shifts. Promising first steps have been made with recent ISOLTRAP measurements of the masses of proton rich Rb and Sr isotopes at ISOLDE [62] (including the rp-process waiting point ^{76}Sr and ^{74}Rb with a half-life of 64 ms), and the recent mass measurements of rp-process nuclei in the V–Mn range in the ESR storage ring at GSI [63]. The latter method allows in principle mass measurements of exotic nuclei with half-lives as low as 10 μs. Among the most critical data are masses of nuclei that have been shown to be proton unbound, such as ^{69}Br and ^{73}Rb. Mass measurements for these nuclei could be done using neutron transfer reactions or neutron stripping reactions with intense radioactive beams of ^{70}Br and ^{74}Sr as they will for example be available at MSU/NSCL. To extend such measurements on proton unbound nuclei towards heavier nuclei requires the higher radioactive beam intensities at next generation facilities like RIA. Half-life measurements of ^{74}Sr and ^{96}Cd would also be important.

2.1.2. Data needs for the rp-process — reaction rates

In the rp-process proton-capture rates are only important when they act on low equilibrium abundances (for example in $2p$ capture reactions [7]), when they compete with α induced reactions (in the αp process), at burst ignition, or during freeze-out when temperatures and proton abundances drop and proton captures compete with β decays. In principle, statistical model calculations like NON-SMOKER [64] or MOST [65] allow rate calculations with accuracies of about a factor of two. This has been shown for a number of stable Sr, Y, Zr, Nb, Ru, Pd, and Sn isotopes (see for example [66–68]). However, the statistical model can only be applied if the level density at the Gamow window in the compound nucleus is sufficiently high [69]. In some cases along the rp-process path this is not the case. Examples include the CNO breakout reactions as well as the ^{56}Ni$(p,\gamma)^{57}$Cu and ^{64}Ge$(p,\gamma)^{65}$As bottle necks. In those cases, experimental information from radioactive beam experiments complemented with accurate theoretical calculations on resonance energies and spectroscopic factors are needed. There has been significant progress in a few cases, for example in the case of ^{56}Ni(p,γ), where radioactive beam experiments at TAMU [70] and ANL [71] have shed light on the properties of low lying resonances and together with shell model calculations [73, 74] reduced the uncertainties in the proton capture rate dramatically. See [72] for a recent compilation of reaction rates on unstable nuclei in the $A = 20$–40 range.

Overall, however, for the vast majority of the low level density reaction rates along the rp-process path experimental information is very sparse and the rates are therefore highly uncertain. For these reactions radioactive beam experiments offer the unique opportunity to measure rates directly in inverse kinematics at the relevant low energies of the order of 0.1–1 MeV/u. For a few important reaction rates first direct measurements with radioactive beams have been performed in pioneering experiments, mainly at Louvain-la-Neuve (for example [75]) and ANL (for example [76]). With these experiments important information on the reaction rates was obtained, but low beam intensities prevented measurements over the whole relevant temperature range between 0.05 and 0.4 GK. Many orders of magnitude more beam intensity will be necessary to obtain reliable data for the important reaction rates at all relevant temperatures. Such beam intensities will be available to some extent at the new ISAC facility and for example at the planned RIA accelerator. For the foreseeable future, direct low energy measurements of reaction rates will have to be complemented with more sensitive indirect techniques like proton scattering [77], transfer reactions and Coulomb breakup [78] which to a large extent involve radioactive beams as well. This requires a complementary approach with different experiments at various types of radioactive beam facilities. For example, for Coulomb Breakup and some transfer reaction studies fast beam fragmentation type facilities like GSI or the new MSU/NSCL Coupled Cyclotron Facility are needed. In addition a number of lighter radioactive nuclei in the rp- and αp-process path can be studied via transfer reactions from stable nuclei (see for example [79]). This complementary approach, therefore, also has to include stable beam experiments.

2.1.3. Data needs for the rp-process — level structure

Finally, rp-process models are also affected by the existence of isomers or the thermal population of excited states changing effective β decay and proton capture rates. Knowledge of such states is also crucial for the correct interpretation of β and proton decay lifetime measurements. Preliminary studies seem to indicate that the direct effects on rp-process calculations are rather small [7, 80] but clearly more theoretical work needs to be done to study the sensitivities in all the relevant cases.

2.2. Nuclear physics of crust processes

Most of the accreted matter remains on the surface of the neutron star once the thermonuclear burning is over. The subsequent fate of the rp-process ashes is characterized by a steady increase in pressure from the ongoing accretion of material onto upper layers. While the rp-process ashes gradually replaces material in the neutron star crust, the steady increase in pressure leads to non-equilibrium nuclear processes driving the matter neutron rich. Haensel and Zdunik 1990 [81] provided a first calculation of the sequence of nuclear processes assuming a cold neutron star and pure helium flashes on the surface producing solely ^{56}Ni as an initial composition. They found that the rising electron Fermi energy stepwise triggers electron capture reactions until after typically 100 yr (for an accretion rate of $10^8\ M_\odot/\mathrm{yr}$) neutron drip density is reached. At this point the composition of the crust is ^{56}Ar. Deeper in the crust, beyond neutron drip, further electron captures are associated with the emission of typically 6 neutrons per capture reaction. This leads to the formation of lighter nuclei along the neutron drip line until pycnonuclear fusion reactions (fusion reactions induced by large density, not temperature — for example the fusion of ^{34}Ne into ^{68}Cr) again synthesize heavier nuclei (see Fig. 2).

However, recent rp-process calculations with extended nuclear reaction networks show that on most accreting neutron stars, including X-ray pulsars, combined hydrogen and helium burning via the αp and rp-processes occurs. In this case, the rp-process ashes has been found to be a mixture of various nuclei in the $A = 64$–106 range with only small amounts of ^{56}Ni. Therefore, in most systems the common description of the crust of an accreting neutron star as a single species (at a given depth) lattice with small impurities breaks down. One of the consequences is that the thermal conductivity of the crust is drastically reduced and temperatures in the crust are significantly higher than previously assumed [82]. Likewise, the electrical conductivity of the crust is reduced, thereby increasing ohmic diffusion timescales for the currents responsible for crust magnetic fields [23].

While these pioneering studies represent an important first step, they so far have been based on very simplified treatments of the underlying nuclear physics. In order to link neutron star models with astronomical observables, improvements in the relevant nuclear data and their implementation in neutron star crust models are needed. The most critical nuclear physics data are

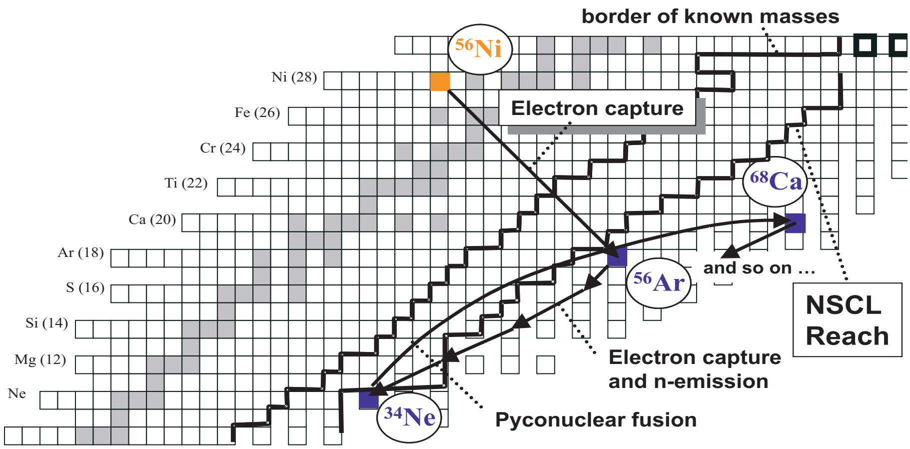

Fig. 2. The begin of the sequence of crust reactions in a fluid element as it is compressed by the ongoing accretion and therefore moves continuously deeper into the crust. Here it is assumed that the initial composition is ^{56}Ni [81]. Also shown is the border of known masses and the reach for mass measurements at the new NSCL Coupled Cyclotron Facility at MSU.

β strength functions and nuclear masses that both determine the electron capture rates. These data are needed for a large number of nuclei in the mass range $A \approx 20$–106 from stability to the neutron drip line.

Fig. 2 shows the mass range in question together with the border of experimentally known nuclear masses. Clearly, mass measurements at radioactive beam facilities are necessary to reliably calculate electron capture Q-values. While the border of known masses can be pushed closer to the neutron drip line by existing radioactive beam facilities (see for example the reach of the MSU/NSCL Coupled Cyclotron Facility in Fig. 2), a next generation facility such as the proposed RIA accelerator is needed to put crust model calculations on a solid experimental basis.

In addition, β-strength distributions for electron capture on neutron rich nuclei are needed to calculate the electron capture rates. These states cannot be populated in decay experiments and the relevant strength functions have to be determined via charge exchange reactions. For stable nuclei this has been done for a large number of cases via (n,p) reactions at TRIUMF and Studvik. However, for unstable nuclei no experimental information on Gamow–Teller strength distributions is available. Here, radioactive beam experiments could make a significant contribution by measuring strength functions in inverse kinematics, for example via the $(t,^3\mathrm{He})$ reaction, which has been shown to yield equivalent information at sufficiently high energies (above 80–100 MeV$/u$). The lack of data is most severe for odd–odd nuclei, where no experimental data exist. Model calculations, therefore, have to rely on theoretical predictions of electron capture rates. Here, progress is needed as well. While several data sets based on parametrizations [83] or global QRPA calculations [84] exist, none of them covers the complete range of nuclei relevant for neutron star crust processes. Furthermore, recent large scale shell model calculations of Gamow–Teller β-strength functions for odd-odd fp-shell nuclei showed especially large deviations in the position of the Gamow–Teller resonance compared to other predictions [85]. Experimental data are clearly needed to clarify this issue.

3. Summary

Progress in our understanding of nuclei far from stability is needed for the interpretation of observations from accreting neutron stars. This progress requires a complementary and coherent effort of nuclear theorists and experimentalists at various different types of radioactive beam and stable beam facilities targeting a large number of nuclei with $A \leq 106$ and ranging from the proton drip line to the neutron drip line. While there are exciting new experimental opportunities at existing accelerator facilities that will lead to significant progress, a next generation facility like RIA is needed to put model calculations for accreting neutron stars on a solid nuclear physics basis.

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