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# The rp process and x-ray bursts

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I briefly review recent advances in our understanding of X-ray bursts in observations, theory, and nuclear experiments.

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## 1. Introduction

X-ray bursts are among the most exciting explosive astrophysical phenomena in our Galaxy [1, 2, 3, 4]. With dozens of sources bursting regularly, or irregularly with recurrence times of hours to days they are the most frequent thermonuclear explosions we know of. The brightness, frequency, and the fact that the same source can be repeatedly observed with different telescopes makes them a unique testing ground for explosive nuclear burning at extreme temperatures and densities. X-ray bursts occur on the surface of neutron stars accreting matter from a close companion star. X-ray bursts and the associated phenomena provide therefore a unique window into the physics of neutron stars. Not only do they probe neutron stars in different ways, but unlike isolated neutron stars that are constrained in properties by the formation mechanism, the mass accretion process changes spin, mass, and thermal structure of the neutron star considerably broadening the parameter space for neutron star studies.

X-ray bursts occur in a layer of often hydrogen and helium rich material that is accreted onto the surface of the neutron star. After a few hours of accretion the material ignites and hydrogen and helium burn into heavier elements in a thermonuclear explosion that typically lasts for 10-100 s. The released nuclear energy heats the surface layers to temperatures where thermal X-rays are emitted from a photosphere. This results in an observable X-ray burst with a typical energy of $10^{39}$-$10^{40}$ ergs.

There are many open questions concerning the variety of burst timescales and shapes, recurrence time behavior, and the role of multidimensional effects such as ignition points, the spreading of the burning front across the star, or the role of rotation. In addition, a range of discoveries and new observational data by X-ray observatories such as Beppo-SAX, RXTE, Chandra, and XMM-Newton, have revolutionized this field and dramatically broadened the range of known nuclear physics driven phenomena. Examples include the discovery of millisecond oscillations during X-ray bursts [3], the detection of absorption lines that provide information on the surface composition and the gravitational redshift [5], and the discovery of superbursts - extremely rare but about a factor of 1000 more powerful X-ray bursts [6].

To interpret these phenomena and to address the many open questions the astrophysics as well as the underlying nuclear physics need to be understood. Data from observations and from experimental nuclear physics are therefore needed. On the observational side, data have reached an unprecedented level of accuracy. An example are X-ray burst light curves from GS 1826-24. Because this is a relatively regular burst source, long term observations of many bursts can be combined to improve statistics. As a consequence, burst profiles can be measured with accuracies of a few percent. For GS 1826-24 this clearly revealed small changes in the burst profile over a period of several years, most likely driven by changes in the accretion rate [7]. When combined with accurate nuclear physics such observations would provide precision tests for X-ray burst models. However, as [8, 9] showed, nuclear physics uncertainties in X-ray burst models still exceed the observational precision by far.

Recent progress in theory has led to predictions of additional signatures of the nuclear burning during X-ray bursts. It has been shown that ejection of some burned material during winds in particularly luminous radius expansion bursts could lead to observable signatures in the X-ray spectra [10]. This is discussed in more detail in section 3. In addition it has been found that the detailed composition of the burst ashes can greatly influence nuclear heating in the crust (see Ed Brown et al. and Becceril et al. contributions to these proceedings and [11]). This directly affects the ignition conditions for superbursts [12, 13]. It also influences the thermal profile of the neutron star crust, which is relevant for observations of the cooling of neutron stars in certain types of transients (see [14] for a review and [15] for a recent example). In these systems periods of mass accretion alternate with periods of quiescence where the accretion shuts off. During the accretion phase the neutron star is heated by nuclear processes in the crust transforming the ashes of the X-ray bursts and superbursts occuring on the surface. During quiescence the cooling of the neutron star can then be observed for many years. This probes the thermal structure of the neutron star and can provide critical constraints for the core cooling mechanism. This in turn provides clues about the core composition and the possible existence of quark or pion condensates.

In summary, experimental data on the nuclear physics of X-ray bursts are needed to:

- understand the wide variety of observed X-ray burst light curves and interpret them to test X-ray burst models and to constrain system properties such as the accreted composition. For example, the amount of hydrogen in the accreted matter is critical for determining distances [16] and to constrain the neutron star compactness and the equation of state for dense nuclear matter [17]. The reason is the dependence of the Eddington luminosity - the maximum luminosity where radiation pressure balances gravity - on the composition of the surface material. X-ray burst observations could address this issue as the shape of the burst light curve depends sensitively on the amount of hydrogen present at ignition. Therefore, the accreted composition could be constrained by comparing observed bursts with model calculations, provided the burst models are reliable and the underlying nuclear physics, which also shapes the light curve [18, 19, 20, 8, 9], is understood.

- calculate possible observational signatures from material ejected during X-ray bursts, and to interpret possible future observations of such signatures

- reliably calculate the composition of the burst ashes deposited on the neutron star surface. This is needed to understand all processes that occur deeper in the crust, such as superbursts or crustal heating.

In the following section I will discuss in more detail recent advances in our understanding of the nuclear physics of X-ray bursts. In section 3 I will then review recent theoretical progress concerning mass ejection in X-ray bursts.

## 2. Nuclear physics needs

The nuclear processes driving X-ray bursts are the $3\alpha$, $\alpha$p- and rp-processes [21, 22, 4] proceeding along the proton dripline, in some bursts up to Te [20, 9]. Masses, half-lives, and reaction rates for (p,$\alpha$) and ($\alpha$,p) reactions on unstable nuclei are important. See [23, 22, 24, 4] for more general reviews, [25] for the importance of masses, [26] on breakout reactions from the CNO cycles, and as an example [27, 28] for the importance of a single reaction rate - in this case $^{15}$O($\alpha$,$\gamma$).

The vast majority of half-lives along the rp-process path have already been measured, and most of the masses are coming within reach at existing facilities. A number of radioactive beam facilities operate now Penning traps, where precision mass measurement programs near or in the path of the rp-process have begun or continue. Examples include the CPT at ATLAS [29], ISOLTRAP at ISOLDE [30], LEBIT at MSU, SHIPTRAP at GSI or JYFLTRAP at Jyväskylä [31]. In general, mass measurements have already progressed far enough so that the remaining unknown masses needed for rp-process calculations can be obtained from mass extrapolations [32] or, beyond the $N = Z$ line, from Coulomb shift calculations [8]. While mass uncertainties are still a problem and measurements are urgently needed, rp-process calculations do not depend anymore on global mass models, in stark contrast to the modeling of the r-process.

The experimental advances in mass measurements have already led to important progress in the understanding of X-ray bursts. For example, mass and lifetime measurements around the key waiting point nuclei $^{64}$Ge, $^{68}$Se, and $^{72}$Kr have already established that together these nuclei are likely to impose considerable delays in the rp-process (see [25] for a review). This has led to the interpretation of frequently observed rather long X-ray bursts ( 100s) as signatures for an extended rp-process, and therefore for the presence of significant amounts of hydrogen at ignition. This constrains the burning regime, the nature of the companion star (hydrogen rich) and can improve distance estimates as the maximum possible burst luminosity is determined by the composition of the accreted material.

However, most of the charged particle rates in the rp-process are still based exclusively on theory, and in most of the remaining cases experimental information needs to be complemented with theory. Theoretical predictions of rp-process reaction rates are not sufficient. Shell model calculations, which can be used up to $A \approx 60$, can predict excitation energies of resonant states [33, 34]. However, reaction rates are so sensitive to resonance energies that the rather small uncertainties in the shell model predictions of around 100 keV still can translate into reaction rate uncertainties of many orders of magnitude. In addition, alpha strengths and the weak proton strength of some important resonances are difficult to calculate accurately. Beyond $A \approx 60$ statistical models are used to predict reaction rates, even though level densities near the proton dripline are too small for such an approach to be applicable [35]. It is therefore essential to determine reaction rates experimentally.

Direct measurements of charged particle induced reaction rates on unstable nuclei using radioactive beams and inverse kinematics techniques have been difficult because of limited beam intensities (see review in [4]). In particular, proton capture rates require beam intensities in excess of $10^{7-8}$ pps, often much more. Measurements have only been possible in a few cases, for example the measurement of the $^{13}$N(p,$\gamma$) reaction rate at Louvain-La-Neuve [36], or the measurements of the $^{21}$Na(p,$\gamma$) and $^{26}$Al(p,$\gamma$) reaction rates at TRIUMF [37, 38]. Also, direct measurements are only possible when the reaction is dominated by the ground state contribution of the target nucleus and not by excited states thermally populated in the stellar environment. This is usually the case, but not always [39].

The use of indirect techniques that provide information that helps to reduce the uncertainty of reaction rate calculations is therefore of great importance. [4] give an overview over some of the techniques that have been used recently using stable and radioactive beams. We developed a technique at Michigan State University's National Superconducting Cyclotron Laboratory (NSCL) based on fast radioactive beams, that can be used to provide precise excitation energies of resonant states for rp-process nuclei using (p,d) reactions in inverse kinematics [40, 39]. States of interest are identified by the detection of in-beam $\gamma$-rays. This method and recent results are discussed in more detail in the contribution of Galaviz et al. to these proceedings. We therefore only summarize some of the key features here.

One advantage of our technique is the fact that a less neutron deficient beam can be used to populate the nucleus of interest. This gives the method a greater reach into the rp-process path, and, in fact, most of the rp-process reaction rates up to around $A \approx 56$ should be accessible at the NSCL. In addition, the use of mixed beams and event-by-event beam particle identification often allows one to measure several nuclei simultaneously in a single experiment, and also, in some cases, to populate the same nucleus with different reactions. The use of $\gamma$ rays to determine the excitation energies provides the required precision of a few keV. This precision is needed because resonant reaction rates depend exponentially on resonance energies, and uncertainties of only a 100 keV that are typical for shell model predictions, can lead to uncertainties of up to 4 orders of magnitude [40, 39]. Of course, what is needed is the resonance energy, so besides the precision measurement of the excitation energy, the Q-value needs to be known with similar precision. The application of this technique to a broad range of reaction rates therefore has to be coordinated with efforts at Penning trap facilities to measure the relevant ground state masses with keV precision.

Our method does not provide information on states that predominantly decay by proton emission. While many unbound resonant states of relevance have sufficient $\gamma$ branches owing to the Coulomb barrier for protons, some important states are predominantly proton emitters. For such states, charged particle spectroscopy is needed, and a similar technique based on the same types of (p,d) reactions but using d-spectroscopy to determine excitation energies is currently being developed at the NSCL.

While a determination of the resonance energies removes the largest uncertainty in reaction rate estimates, remaining uncertainties, mainly due to spectroscopic factors, still can amount to factors of 2-3. Such uncertainties might be tolerable in many cases, but in some cases they might not. Results from sensitivity studies with X-ray burst models that are currently preformed (see contribution from Amthor et al. to these proceedings) will be able to clarify this. In the cases where a more precise reaction rate is needed, experiments have to constrain the resonance strength further. Besides direct measurements, these could include Coulomb breakup, proton transfer reactions, or neutron transfer reactions to mirror nuclei. Such measurements are also needed in reactions closer to stability when the level density is too high to clearly match shell model states with observed states, or states from the mirror nucleus.

## 3. Ejection of Burst Ashes

A long standing question concerning X-ray bursts is the possibility of the ejection of burned material into space. This is important to determine a possible contribution of X-ray bursts to Galactic nucleosynthesis. There has been interest in this question in order to explain the still unknown origin of the neutron deficient Mo and Ru isotopes in the solar system. Current p-process models can explain the origin of most of the neutron deficient so called p-isotopes in nature, but not the unusually large abundances of $^{92,94}$Mo and $^{96,98}$Ru [41]. One possibility would be the rp-process in

X-ray bursts, which has been shown to produce these isotopes, provided sufficiently large amounts of burst ashes can be ejected into space [22, 4]. In addition, the detection of elemental signatures in the spectral features of X-ray bursts, which has become possible in some cases [5, 42], would provide unique constraints on the nuclear burning processes in X-ray bursts if created by ejected burst ashes.

Clearly the ratio of nuclear energy (at most $\approx 5$ MeV/u) to gravitational binding energy on the neutron star surface ($\approx 200$ MeV) allows to eject at most a few percent of the accreted matter in the most favorable case. Observed X-ray bursts often exhibit radiation pressure driven expansions of the photosphere leading to a reddening of the spectrum and an increase in the radius of the emission area. It is very likely that in such bursts radiation driven winds develop (for example [43]). So the key question is whether the few percent of the accreted matter that can be ejected in radiation driven winds during photospheric radius expansion (PRE) bursts contain burst ashes or whether they are merely the unmodified top layer of accreted material. The answer depends on the extent of the convection zone that develops during an X-ray burst and transports burned material towards the surface. After burst ignition, a steep temperature profile develops near the ignition zone that drives a growing convection zone. As the outer layers heat up and the burst becomes observable, the temperature profile flattens and the convection zone retracts. Eventually convection stops before the peak of the burst is reached (see for example Fig. 25 in [9]).

Weinberg et al. [10] recently addressed this question in an analytical model calculating the evolution of the convection zone during an X-ray burst. Such an approach was necessary, as the zone resolution in 1D X-ray burst models is not sufficient to determine whether the convection zone reaches far enough into the thin outer mass layer that can be expelled by a wind. Weinberg et al. [10] find that for a wide range of accretion rates and accreted compositions the convective zone indeed extends far enough into the outer layers of the neutron star to eject burst ashes in a radiation driven wind during a PRE burst. The effect is strongest for lower accretion rates, and for systems that accrete little hydrogen. The reason is the same - in both cases the burst ignition and energy generation is dominated by pure He burning, which generates heat more quickly through a faster $3\alpha$ rate and therefore drives a more extended convection zone.

The material ejected in X-ray bursts is not necessarily the ashes of the rp-process produced at the end of the burst, but reflects the composition of the burning layer at the time the convection zone retracts and deposits its material in the outer layers of the accreted atmosphere. This occurs before and during the rise of the burst before a full reaction flow past $^{56}$Ni develops. Also, helium is always present during this phase and the nuclei have low enough $Z$ for ($\alpha$,p) or ($\alpha,\gamma$) reactions to be faster than $\beta$-decays. Therefore, even when hydrogen is present, an rp-process does not yet develop at this early stage of the burst. The composition of the wind depends sensitively on the actual amount of material ejected as the composition in the convection zone changes rapidly with time establishing steep composition gradients with depth during its retreat.

The nuclear processes producing the ejected material depend on the amount of hydrogen present in the convection zone. When hydrogen and helium are accreted a large amount of hydrogen is available as catalyst for the $\alpha$p-process, a sequence of ($\alpha$,p) and (p,$\gamma$) reactions up to the $Z \approx 20$ range. As for most (p,$\gamma$) reactions there is an ($\alpha$,p) reaction hydrogen is hardly consumed but needs to be present to enable the process. The ejected composition is typically dominated by $^{28}$Si and $^{24}$Mg besides helium, which always dominates. Proton captures on iron present in the accreted material leads to a small but significant production of $^{60}$Zn and $^{62}$Zn.

For the case of pure helium the reaction flow is much more limited because of the lack of hydrogen. Nevertheless, the reaction sequence is not a simple chain of $\alpha$ captures starting with the 3$\alpha$ reaction and continuing with ($\alpha$,$\gamma$) reactions beyond $^{12}$C as one could naively expect. Such a chain would tend to produce large amounts of $^{12}$C because of the relatively slow $^{12}$C($\alpha$,$\gamma$)$^{16}$O reaction. Instead, the $^{12}$C($\alpha$,$\gamma$)$^{16}$O reaction is bypassed by the much faster reaction sequence $^{12}$C(p,$\gamma$)$^{13}$N($\alpha$,p)$^{16}$O. This reaction sequence requires the presence of a small amount of protons (about $10^{-9}$ mass fraction) serving as catalysts, which are generated by ($\alpha$,p) reactions mainly on $^{24}$Mg, $^{32}$S, and $^{36}$Ar. These nuclei are predicted to have significant ($\alpha$,p) branchings. Once the bypass sets in, a positive feedback loop is established as the more rapid production of heavier nuclei accelerates the proton producing ($\alpha$,p) reactions on $^{24}$Mg, $^{32}$S, and $^{36}$Ar, which in turn further accelerates the bypass. This makes the $^{12}$C(p,$\gamma$)$^{13}$N($\alpha$,p)$^{16}$O bypass a very robust feature of any helium burning scenario where temperatures exceed 1 GK.

For such temperatures the $^{12}$C($\alpha$,$\gamma$)$^{16}$O reaction is presumably the slowest reaction in the chain of $\alpha$-reactions up to $^{32}$S. The bypass therefore leads to a considerable acceleration of the reaction flow towards heavier nuclei with a rather sudden onset. One important consequence is the destruction of most $^{12}$C and the production heavier nuclei. Therefore the X-ray burst ejects, besides of $^{4}$He, mostly $^{32}$S and $^{28}$Si instead of $^{12}$C. In addition, the sudden onset of the bypass reaction sequence at temperatures around 1 GK leads to an energy burst, which drives the convection zone further out for a longer time. The bypass also leads to the rapid establishment of a proton abundance, which leads to additional proton captures and the production of nuclei off the $\alpha$ chain. In particular, proton capture on iron present in the accreted composition also occurs for pure helium accretors and leads to the production of a significant amount of $^{58}$Fe and $^{59}$Co in the ejected ashes.

As Weinberg et al. [10] show, the amount of material ejected are sufficient to generate absorption edges in the X-ray spectra that could in principle be detectable with present instruments. For the case of detection in the wind itself, the high $Z$ isotopes in the Co-Zn range produced by proton captures on existent iron seed nuclei produce the dominant features. Their detection would directly probe the amount of protons present in the burning zone. Alternatively, absorption edges could be observed during the X-ray burst in the photosphere of the neutron star once the wind has blown off the outer layers. In this case, signatures from silicon and sulfur should be detectable.

## 4. Summary

X-ray bursts are an exciting area of nuclear astrophysics that is characterized by rapid progress in observations, theory, and experiment. Observations with the large number of currently operating X-ray observatories lead to the discovery of new phenomena at a rapid pace. Advances in theory allow one now to include all the relevant nuclear physics in full 1D X-ray burst model calculations. New analytical models have predicted new observable signatures of the nuclear burning in X-ray bursts to search for. And at the same time rare isotope beam facilities are providing nuclear physics data needed to model X-ray bursts, to interpret observations, and to constrain model calculations by comparison with observations. Nevertheless, the determination of charge particle reaction rates on unstable nuclei remains a major challenge for the field, owing to the limited beam intensities available at existing facilities. A range of next generation facilities is therefore needed to address this challenge and to carry out the broad range of experiments needed to understand X-ray bursts. New facilities on the horizon include the upgrades at RIKEN and GSI/FAIR, the planned low energy beam facility at the NSCL, as well as the NSCL upgrade currently under discussion as one of the possible future rare isotope facilities in the US. TRIUMF/ISAC as the leading ISOL facility will continue to play an important role in this field as well. With these developments there is hope that within the coming decade the most pressing data needs for the simulation of X-ray bursts can be addressed.

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## References

[1] H.W.G. Lewin , J. van Paradijs and R.E. Taam 1997 in *X-Ray Binaries*, edited by W. H. G. Lewin, J. van Paradijs, and E. P. J. van den Heuvel (Cambridge Univ. Press, Cambridge) p. 175

[2] L. Bildsten 2000, "Rossi 2000: Astrophysics with the Rossi X-ray Timing Explorer, March 22-24, 2000 at NASA's Goddard Space Flight Center, Greenbelt, MD USA", E65, (astro-ph/0001135)

[3] T.E. Strohmayer and L. Bildsten 2003, Compact Stellar X-ray Sources, eds. W.H.G. Lewin and M. van der Klis, Cambridge University Press, astro-ph/0301544

[4] H. Schatz and K.E. Rehm *Nucl. Phys. A* **777** 601 (2006).

[5] J. Cottam, F. Paerels and M. Mendez, Nature 420 (2002) 51.

[6] J.M.M. in't Zandt et al. astro-ph/0407087 (2004).

[7] D.K. Galloway D K et al., Ap. J. 608 (2004) 930.

[8] B.A. Brown et al., Phys. Rev. C65 (2002) 5802.

[9] S.E. Woosley et al., Ap. J. Suppl. 151 (2004) 75.

[10] N.N. Weinberg et al, Ap. J. 639 (2006) 1018.

[11] S. Gupta et al., astro-ph/0609828.

[12] E.F. Brown, Ap. J. 614 (2004) 57.

[13] A. Cumming et al., Ap. J. 646 (2006) 429.

[14] R. Wijnands, astro-ph/0405089.

[15] E.M. Cackett et al., astro-ph/0605490.

[16] D.K. Galloway et al., Ap. J. 639 (2006) 1033.

[17] F. Özel, Nature 441 (2006) 1115.

[18] O. Koike, M. Hashimoto , K. Arai and S. Wanajo, Astron. Astrophys. 342 (1999) 464.

[19] F.-K. Thielemann et. al., Prog. Part. Nucl. Phys. 46 (2001) 5.

[20] H. Schatz et al., Phys. Rev. Lett. 86 (2001) 3471.

[21] R.K. Wallace and S.E. Woosley, Ap. J. Suppl. 45 (1981) 389.

[22] H. Schatz et al., Phys. Rep. 294 (1998) 167.

[23] A.E. Champagne and M. Wiescher, Ann. Rev. Nuc. Part. Sci. 42 (1992) 39.

[24] M. Wiescher, H. Schatz and A.C. Champagne, Phil. Trans. Roy. Soc. Lond. 356 (1998) 2105.

[25] H. Schatz, astro-ph/0607625.

[26] M. Wiescher, J. Goerres, and H. Schatz, Journ. Phys. G 25 (1999) R133.

[27] J.L. Fisker, J. Goerres, M. Wiescher and B. Davids, astro-ph/0410561, to be published in Ap. J. (2006).

[28] R.L. Cooper and R. Narayan, astro-ph/0608068.

[29] J.A. Clark et al., Phys. Rev. Lett. 92 (2004) 192501.

[30] D. Rodriguez et al., Phys. Rev. Lett. 93 (2004) 161104.

[31] A. Kankainen et al., Eur. Phys. Journ. 29 (2006) 271.

[32] G. Audi, A.H. Wapstra and C. Thibault, Nucl. Phys. A729 (2003) 337.

[33] H. Herndl et al. Phys. Rev. C52 (1995) 1078.

[34] J.L. Fisker et al. Atomic and Nucl. Data Tab. 79 (2001) 241.

[35] T. Rauscher, F.-K. Thielemann and K.-L. Kratz Phys. Rev. C56 (1997) 1613.

[36] P. Decrock et al. Phys. Lett. B304 (1993) 50.

[37] S. Bishop et al., Phys. Rev. Lett. 90 (2003) 162501.

[38] C. Ruiz et al.. Phys. Rev. Lett. 96 (2006) 252501.

[39] H. Schatz et al., Phys. Rev. C72 (2005) 065804.

[40] R.R.C. Clement et al., Phys. Rev. Lett. 92 (2004) 2502.

[41] M. Arnould and S. Goriely, Phys. Rep. 384 (2003) 1.

[42] A.M. Juett, D. Psaltis and D. Chakrabarty, Ap. J. 560 (2001) L59

[43] B. Paczynski and M. Proszynski, Ap. J. 302 (1986) 519.