X-RAY BURSTS AND PROTON CAPTURES CLOSE TO THE DRIPLINE

T. Rauscher[1], F. Rembges[1], H. Schatz[2], M. Wiescher[3], F.-K. Thielemann[1]

The hydrogen-rich accreted envelopes of neutron stars in binary systems are the site for the rapid proton capture nucleosynthethic process (*rp* process), which involves nuclei close to the proton dripline. An overview of the relevant reactions and nuclear properties for *rp*-process studies is given, along with motivations of further experimental nuclear physics studies.

1 Introduction

In low-mass binary systems involving a neutron star, proton-rich material from the atmosphere of the companion giant star can be accreted on the surface of the neutron star [1, 2, 3, 4]. (see also the review article [5]). Once a critical density ($\approx 10^6$ g/cm^3) is reached within the accreted layer, thermonuclear fusion of hydrogen and helium is ignited and high temperatures are attained in an explosive runaway. Such thermonuclear flashes can be observed as so-called type I X-ray bursts. The energy is generated by hot hydrogen burning cycles and by burning helium in the 3α reaction and a sequence of (α,p) and (p,γ) reactions, which provide seed nuclei for the subsequent hydrogen burning in the *rp* process, consisting of rapid proton captures and β^- decays close to the proton dripline. The timescale of the *rp* process is given by the slow electron capture half-lives (waiting points) in the process path.

For a long time the doubly magic nucleus ^{56}Ni ($t_{1/2} = 2 \times 10^4$ s) was considered to be the endpoint of the *rp* process. The reaction network was extended up to Sn in a recent one-zone model calculation [6], and it was found that ^{56}Ni only becomes a temporary waiting point at the initial rise of the burst but that the reaction flow can go beyond in the cooling phase. Thus, nuclei in the mass range $A \approx 80 - 100$ can be synthesized within the short timescale ($\approx 10 - 100$ s) of the explosive event. This results in an enhanced energy production, additional hydrogen consumption and altered ashes of the *rp* process, which are deposited on the crust of the neutron star. If mass ejection during the burst is feasible, this would also open up a new possible explanation of the so-called *p* nuclei in the solar abundance pattern, which are stable proton-rich nuclei which cannot be produced in the *s* and *r* processes.

Of particular importance proved to be two-proton capture reactions which can bridge the waiting points encountered at the $N = Z$ nuclei ^{64}Ge($t_{1/2} = 64$ s), ^{68}Se($t_{1/2} = 36$ s), and ^{72}Kr($t_{1/2} = 17$ s).

---

[1] Department of Physics and Astronomy, University of Basel, 4056 Basel, Switzerland
[2] GSI, Darmstadt, Germany
[3] Department of Physics, University of Notre Dame, Notre Dame, IN, USA

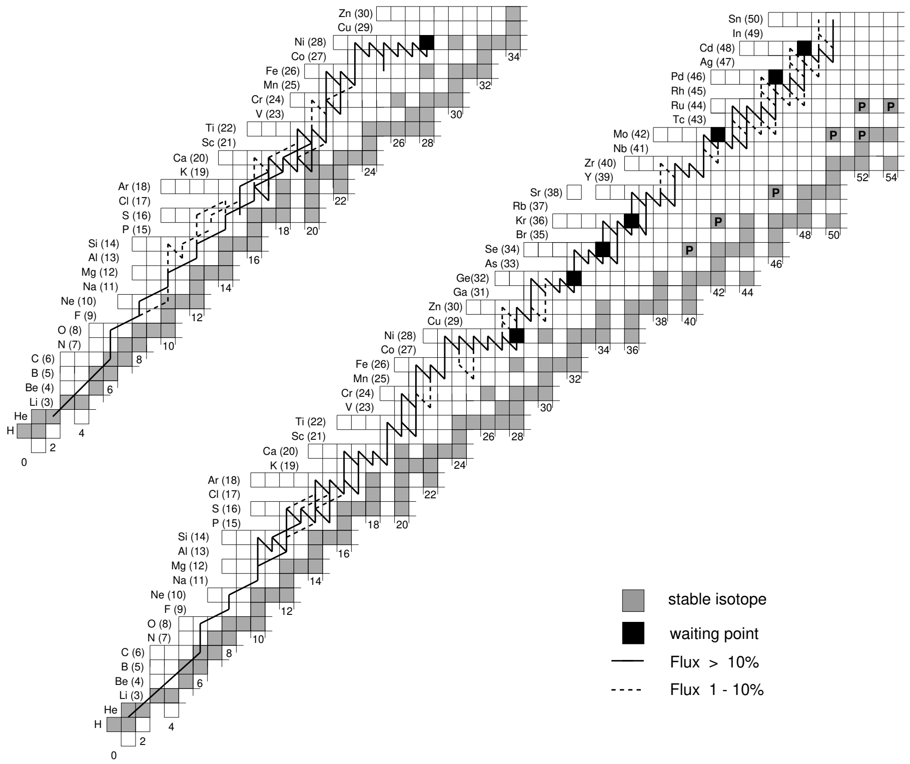

Fig. 1. The *rp*-process reaction-flux integrated over the thermonuclear runaway (top) and the cooling phase (bottom) of a single X-ray burst [6]. Stable *p* nuclei (which cannot be produced in the s and r process) are marked by **P**.

Time-dependent calculations with coupled full networks are currently performed to give a more consistent understanding of the time structure of burst and interburst phases, and of the fuel consumption [7, 8, 9].

2 Proton capture reactions

The reaction path of the *rp* process is shown in Fig. 1. Similar to the *r* process, far away from stability the *rp*-process path is determined by the nuclear masses or proton separation energies, respectively, and the β^--decay half-lives alone and not by individual reaction rates. Only several individual (p,γ) and (p,α) reactions in the early burst phase and the 2p-capture reactions ^{56}Ni(2p,γ)^{58}Zn, ^{64}Ge(2p,γ)^{66}Se, ^{68}Se(2p,γ)^{70}Kr, and ^{72}Kr(2p,γ)^{74}Y will have major impact on the resulting reaction flow, energy generation, and nucleosynthesis. Although the 2p-capture rates are slow due to the short lifetime of the proton-unbound intermediate nucleus after the first capture, they are essential for the continuation of the reaction path because they compete with quite slow β^- decays. Current estimates of these rates at the waiting points are based on mass models and level density calculations. As the rates and derived lifetimes against proton capture depend sensitively on the reaction Q value, more experimental data about nuclear masses in this region are clearly needed to confirm the results. For instance, the stellar lifetime (including β decay and proton capture) of ^{68}Se is

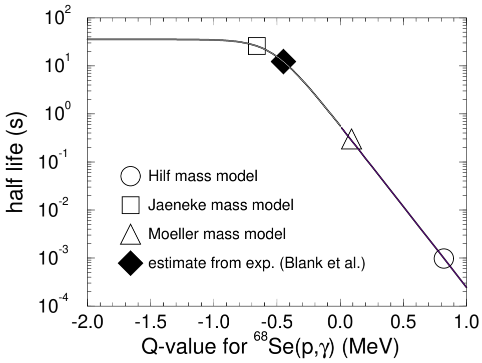

Fig. 2. Stellar halflife (including β decay *and* p-capture) of ^{68}Se as a function of reaction Q value for a temperature of 1.5 GK, a density of 10^6 g/cm^3, and solar hydrogen abundance [6]. Q values predicted by different mass models are indicated.

shown in Fig. 2 as a function of the proton capture Q value. A change in the Q value of only 200 keV, well within mass model uncertainties, might change the stellar lifetime by a factor of 5. Put in another way: For a lifetime determination to better than a factor of 2, the Q value has to be known with an accuracy of better than 100 keV, which is way beyond the accuracy of modern mass model predictions. While a direct study of 2p-capture reactions is not possible, the study of Coulomb dissociation of ^{66}Se, ^{70}Kr, and ^{74}Y offers a way to obtain information about the reactions [10].

In the early burst phase, hot hydrogen cycles are formed which consist of two subsequent proton captures, a β decay, another proton capture and β decay, and a final (p,α) reaction closing the cycle. With rising temperature, these cycles break up by (p,γ) reactions in the order of decreasing Q values. Most of these rates can be predicted in the statistical model of nuclear reactions, as the prerequisite of a sufficient number of resonances within the Gamow window is met [11, 8]. Only at the low proton separation energies close to the dripline, the level density becomes too low to justify averaging over resonances and the contribution of isolated resonances has to be taken into account. Nevertheless, measurements of reactions are highly desireable in all cases, in order to obtain information on the level density and to verify the theoretical calculations [6, 12].

Recently, a study on the influence of proton capture on ^{27}Si, ^{31}S, ^{35}Ar, and ^{39}Ca on hot hydrogen burning became available [13]. Estimates of the rates are given, based on previously published values or updated nuclear properties. The rate used for ^{31}S(p,γ)^{32}Cl [14] is more than a factor of 3 slower than the one previously used [15] in *rp*-process calculations, whereas the other rates differ by about 30%. (Note, however, that the ^{31}S(p,γ) rate is also in disagreement with another recent evaluation [16].) A self-consistent time-dependent calculation [9, 17] shows the importance of these rates in the initial phase of the burst

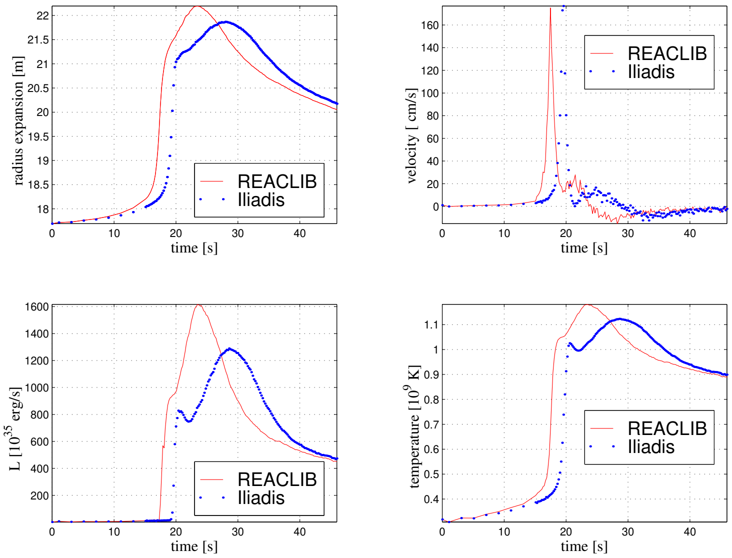

Fig. 3. Comparison of burst profiles with previous rates (REACLIB) [15] and the rates given in [13] (Iliadis) in a self-consistent model [9, 17]. Due to the slower rates, the onset of the burst is delayed, reflected in a delay in the expansion, the luminosity and the temperature profile. Energy generation is suppressed, shown by the lower maxima in luminosity and temperature.

(Fig. 3). Due to the slower rates, the onset of the thermonuclear runaway is delayed and the luminosity and temperature profiles are altered. The strongest effect is due to the ^{31}S(p,γ)^{32}Cl rate which is also reflected in the development of the abundances over time, as shown in Fig. 4. This is in contradiction with the (not self-consistent) post-processing study claiming to have found no significant impact [13]. Together with the nuclear physics uncertainties involved, it proves the importance of measuring such reactions in radioactive ion beam facilities.

3 β decays

As mentioned before, the rp-process flow is determined only by the Q values and β^--decay half-lives as long as the temperature is high enough to permit a (p,γ)–(γ,p) equilibrium. Then the processing to heavy nuclei is determined by the lifetime of the waiting point nuclei. The β-decay half-lives of the critical waiting point nuclei are well-known, even when the proton capture Q values are not. The few unknown half-lives encountered below Zr are those of the nuclei reached by 2p captures. Their half-lives will have little impact since the reaction flow is determined by the slow 2p captures. Only beyond Zr, the *rp*-process path fully enters a region of unmeasured β-decay half-lives. Usually, theoretical half-lives from a certain model are adopted in *rp*-process studies, e.g. from QRPA [18], supplemented by shell model calculations [19] in the one-zone model [6] quoted above. Masses also enter crucially. When comparing predictions of different models it is important to not only consider the average

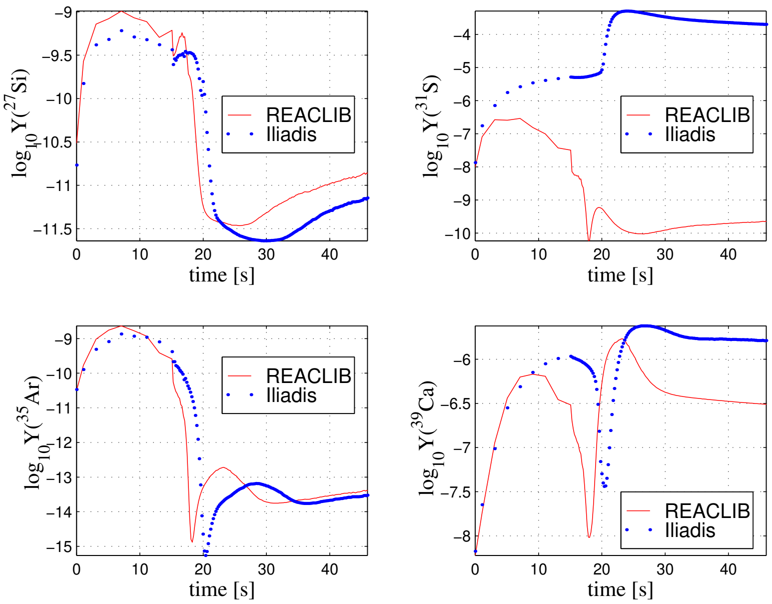

Fig. 4. Abundances of ^{27}Si, ^{31}S, ^{35}Ar, and ^{39}Ca vs. time. Compared are self-consistent calculations [9, 17] with previous rates (REACLIB) [15] and with rates from [13] (Iliadis). The strongest effect is due to the ^{31}S(p,γ)^{32}Cl rate.

global reliability but also the behavior of the uncertainties when the model is extrapolated towards proton-rich nuclei [6].

β-decay half-lives in high temperature scenarios can be altered in respect to laboratory values due to the decay of thermally excited states. It has been shown [18] that the β-decay lifetime of excited states can be significantly different from the lifetime of the ground state. In the *rp* process, this effect could mainly be important for the long lived self-conjugate nuclei, forming the waiting points in the process path. For these nuclei only the population of the first excited 2^+ state plays a role in the relatively low energy regime of $kT \leq 300$ keV of X-ray bursts. The energies of the 2^+ states were estimated in a valence scheme and with shell model calculations [6]. Significant deviations from the ground state decay are only found for ^{64}Ge, ^{68}Se, and ^{72}Kr. However, for temperatures below 2 GK the decay rates stay constant with temperature and around 3 GK the effect is still less than approximately 15% and thus negligible. Only in scenarios with temperatures exceeding 3 GK temperature dependence of β-decay half-lives has to be taken into account.

4 Conclusions

Rapid proton captures along the proton dripline are typical for nucleosynthesis processes at the high density and temperature conditions of an accreted neutron star envelope. Recent investigations have shown that the *rp* process proceeds well beyond Ni and can produce nuclei in the mass range $A \approx 80-100$. To establish the definite endpoint of the *rp* process, further experimental investigations of nuclear properties (masses, β^--decay half-lives, reaction rates) at or close to the dripline are needed. In the lower mass range, reactions of the hot hydrogen burning cycles determine the initial burst phase and the timescale of the processing into more heavy nuclei. Thus, they are interesting targets for current and future studies at radioactive ion beam facilities. For an extensive review on experimental needs and approaches in the *rp* process and in astrophysics in general, see [10]. Consistent multizone, hydrodynamical calculations are important to consider mixing between different layers and to study the influence of the reaction rates on fuel consumption, energy generation and nucleosynthesis in X-ray bursts.

Acknowledgements

This work was supported by the Swiss National Science Foundation (grant 2000-053798.98).

References

[1] S.E. Woosley and R.E. Taam, *Nature* **263** (1976) 101

[2] L. Maraschi and A. Cavaliere, *Highlights of Astronomy* **4** (1977) 127

[3] P. Joss, *Nature* **270** (1977) 310

[4] R. Wallace and S. Woosley, *Ap. J. Suppl.* **45** (1981) 389

[5] W.H.G. Lewin, J. van Paradijs, and R.E. Taam, *Space Sci. Rev.* **62** (1993) 233

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

[7] F. Rembges, M. Liebendörfer, F.-K. Thielemann, H. Schatz, and M. Wiescher, *Stellar Evolution, Stellar Explosions, and Galactic Chemical Evolution,* ed. A. Mezzacappa (IOP, Bristol 1998), p. 495

[8] F. Rembges, C. Freiburghaus, T. Rauscher, F.-K. Thielemann, H. Schatz, and M. Wiescher, *Ap. J.* **484** (1997) 412

[9] F. Rembges, PhD thesis, University of Basel, Switzerland, 1999

[10] F. Käppeler, F.-K. Thielemann, and M. Wiescher, *Annu. Rev. Nucl. Part. Sci.* **48** (1998) 175

[11] T. Rauscher, F.-K. Thielemann, and K.-L. Kratz, *Phys. Rev. C* **56** (1997) 1613

[12] T. Rauscher and F.-K. Thielemann, *At. Data Nucl. Data Tabl.*, to be submitted

[13] C. Iliadis, P.M. Endt, N. Prantzos, and W.J. Thompson, *Ap. J.*, in press

[14] S. Vouzoukas *et al.*, *Phys. Rev. C* **50** (1994) 1185

[15] L. van Wormer *et al.*, *Ap. J.* **432** (1994) 326

[16] A. Lefebvre *et al.*, *Nucl. Phys.* **A621** (1997) 199

[17] F. Rembges *et al.*, *Ap. J.,* in preparation

[18] P. Möller and J. Randrup, *Nucl. Phys.* **A514** (1990) 1

[19] H. Herndl and B.A. Brown, 1997, to be published