The endpoint of the rp-process

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The endpoint of rp-process nucleosynthesis in X-ray bursts determines the fuel consumption, the energy generation, and the abundance pattern of the produced nuclei. To investigate the time structure of rp-process nucleosynthesis, we used a nuclear reaction network including nuclei from H to Sn. We found that if 2p-capture reactions are included, the synthesis of nuclei heavier than Kr proceeds faster than previously thought. Therefore, in most X-ray bursts large amounts of nuclei in the A=80-100 region are expected to be produced. With an escape factor of about 1%, X-ray bursts could account for the large observed solar system abundances of the light p-nuclei like ^{92}Mo and ^{96}Ru that cannot be produced sufficiently in other p-process scenarios.

1. Introduction

Type I X-ray bursts are created by explosive hydrogen and helium burning on accreting neutron stars in low mass binary systems [1]. The energy is generated by burning helium with the 3α-reaction and subsequent helium and hydrogen burning by a series of (α,p) and rapid (p,γ) reactions (rp-process) under high temperature (up to 3 GK) and densitiy (10^6-10^7 g/cm^3) conditions. The nucleosynthesis timescale is determined by the slow β-decay rates (waiting points) along the reaction path. The proton capture Q-value determines, where β-decay occurs. A small proton capture Q-value might hamper further net proton capture because of backprocessing via p-decay (Q<0) or photodisintegration (Q>0). A waiting point will be the endpoint of the rp-process, if it has an effective lifetime several times longer than the X-ray burst timescale, that is of the order of 10-100 s. Depending on the experimentally unknown proton capture Q-values, the rather long lived nuclei ^{64}Ge ($T_{1/2}$=63.7 s), ^{68}Se ($T_{1/2}$=35.5 s) or ^{72}Kr ($T_{1/2}$=17.2 s) have all been previously considered to be the possible endpoints of the rp-process in X-ray bursts.

2. Network calculations

Our nuclear reaction network includes 637 nuclei from H to Sn. All calculations described here were performed with constant temperatures and densities. For reaction rates below Z=32 see [2,3]. Above Z=32 particle induced reaction rates have been calculated using the statistical model code SMOKER and β-decay rates with a QRPA code [4]. Both types of reaction rates depend strongly on nuclear masses, which are in most cases experimentally unknown. For the present calculations we used the Möller et al. mass model [5]. One important exception was made: for ^{68}Se(p,γ) we used the upper limit on the Q-value of -450 keV deduced from the nonobservation of ^{69}Br in some experiments [6,7].

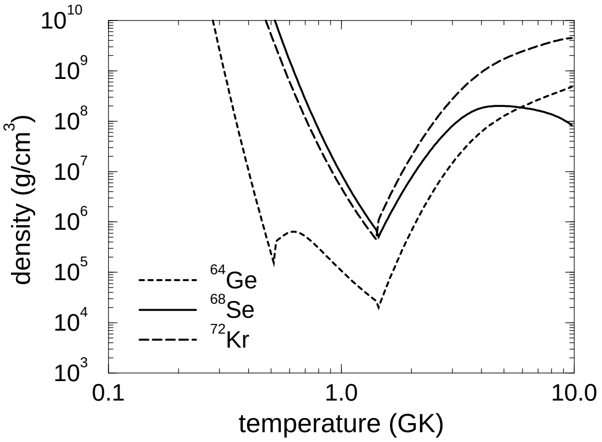

Figure 1. Densities for equal net p-capture and β-decay rate. Above the lines the waiting points are bridged.

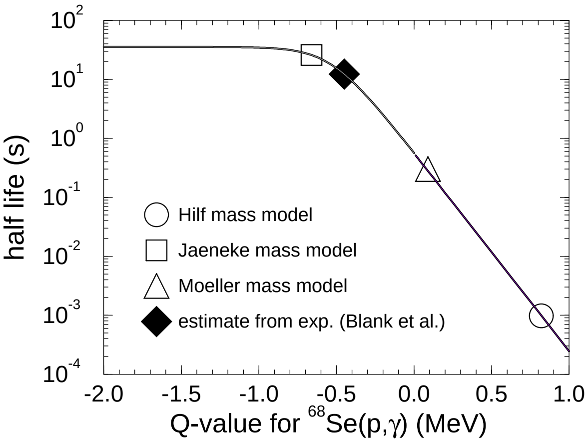

Figure 2. ^{68}Se stellar half life (including β-decay and p-capture) as a function of p-capture Q-value for T=1.5 GK, $\rho=10^6$ g/cm^3.

3. Bridging waiting points

The amount of nuclei heavier than Kr produced in an X-ray burst depends on how effectively the rather long lived isotopes ^{64}Ge, ^{68}Se and ^{72}Kr can be bridged by net proton capture. Figure 1 shows the density where the proton capture rate becomes equal to the β-decay rate as a function of temperature. For densities above the curve proton capture is dominating and the nucleus will not be a waiting point. Since ^{65}As is predicted to be proton bound (128 keV), ^{64}Ge can be bridged very effectively for a wide temperature range assuming densities of 10^6 g/cm^3. On the other hand, ^{69}Br and ^{73}Rb are p-unbound (-450 keV and -311 keV) and have to be bridged by 2p-capture which requires somewhat higher densities. However, Figure 1 clearly shows that for X-ray burst densities between 10^6-10^7 g/cm^3, there is a temperature window between roughly 1 and 2 GK, where proton capture on ^{68}Se and ^{72}Kr is effective. Under these conditions, the timescale for producing elements heavier than Kr will be greatly reduced.

All these conclusions depend strongly on the adopted Q-values for proton capture on ^{64}Ge, ^{68}Se, and ^{72}Kr, which are not known experimentally. We can show this for ^{68}Se in the plot of the stellar half-life (including β-decay and proton capture) as a function of the proton capture Q-value (Figure 2). A change in the Q-value of 200 keV, well within mass model uncertainties, might change the stellar half life by a factor of 5. Note that 2p-capture leads to a significant reduction of the stellar half life for not too negative Q-values. It is therefore not sufficient to demonstrate that ^{69}Br predominantly proton decays in order to conclude that ^{68}Se is a waiting point delaying the reaction flow with its full β-decay lifetime. The behaviour of ^{64}Ge and ^{72}Kr is very similar.

4. Nucleosynthesis timescale

Figure 3 shows the abundance versus processing time for ^{92}Pd, the progenitor of ^{92}Mo, calculated at T=1.5 GK. The A=92 maximum abundance is reached after 55 s for a density of 10^6 g/cm^3. This is 17 s faster than without 2p-capture reactions. At a density of $5{\cdot}10^6$ g/cm^3, 2p-capture reduces the processing time more drastically to 22 s (slightly more p-bound ^{69}As and/or ^{73}Rb would have the same effect). Note that 10% of the maximum abundance is already reached after 30% of the time. Therefore, to produce significant amounts of A=92 material, the X-ray burst temperature has to stay between 1 GK and 1.8 GK for at least 10-50 s. Rise times are usually shorter, but decay time scales are in the 10-100 s range and at the time the temperature drops below 1.8 GK, densities are still of the order of 10^6 g/cm^3 (as we will show in a forthcoming paper). At least in a subset of X-ray bursts we expect the production of large amounts of A=80-100 nuclei.

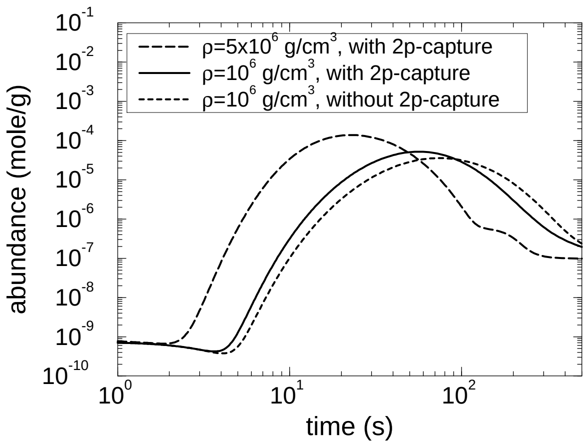

Figure 3. ^{92}Pd abundance as a function of time for T=1.5 GK.

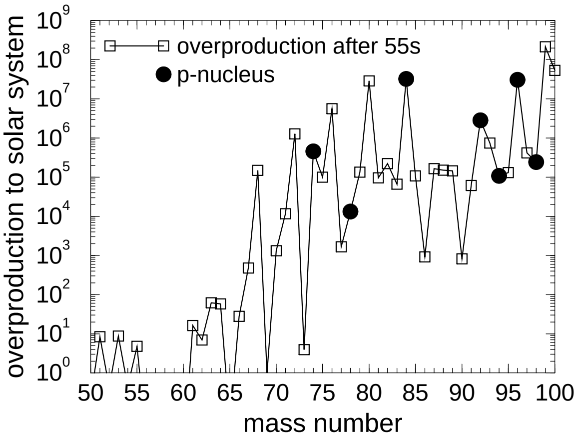

Figure 4. Overproduction factors for T=1.5 GK and $\rho=10^6$ at the time of the ^{92}Pd maximum. The overproduction factors are the sum of all abundances in a mass chain divided by the solar abundance of the most proton rich stable nucleus.

5. Abundance patterns

The resulting overabundance pattern is shown in Figure 4 for the time of maximum ^{92}Pd production. Clearly, the p-nuclei ^{84}Sr, ^{92}Mo and ^{96}Ru can be produced in very large amounts with overproduction factors of comparable orders of magnitude. This is due to the long stellar lifetime of the progenitors ^{84}Mo, ^{92}Pd and ^{96}Cd that are strong waiting points. At higher densities (above 10^6 g/cm^3), more effective 2p-capture on ^{68}Se and ^{72}Kr reduces the production of the corresponding non-p nuclei while it enhances the production of the ^{74}Se and ^{78}Kr p-nuclei. The strong abundance peak for ^{80}Kr (with ^{80}Zr as a progenitor) might cause a conflict with the s-process. Note however, that the overproduction factors depend on the β-decay half lifes of the corresponding progenitors, which are not experimentally known above A=76.

Maximum overproduction factors are generally in the order of 10^7-10^8. To get an order of magnitude estimate for the escape factor that would be required for X-ray bursts to account for observed solar system element abundances, we can assume: a birth rate for an X-ray bursting system of 10^{-5}/yr [8], a lifetime of 10^9 yr [8], a mass transfer rate of 10^{-8}-10^{-9} $M_\odot$/yr [9], a total time for galactic nucleosynthesis of 10^{10} yr, and a galaxy mass of $2{\cdot}10^{11}$ $M_\odot$. This gives an required escape factor of roughly 1%.

6. Conclusions

There are no rp-process endpoints in the A=64-72 region in most X-ray bursts. Processing can therefore proceed into the A=80-100 region and overproduction factors are high enough to make X-ray bursts a possible contributing factor to galactic nucleosynthesis. This could explain some of the large observed light p-nuclei abundances which cannot be produced sufficiently in other p-process scenarios. Mass measurements of ^{65}As,^{68}Se, ^{69}Br, and ^{73}Rb as well as β-decay rate measurements of ^{80}Zr, ^{88}Ru, ^{92}Pd, and ^{96}Cd would greatly improve the accuracy of the predictions.

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REFERENCES

1. R. Wallace and S. Woosley, Ap. J. Suppl. 45 (1981) 389
2. L. van Wormer et al., Ap. J. 432 (1994) 326
3. H. Herndl et al., Phys. Rev. C52 (1995) 1078
4. P. Möller and J. Randrup, Nucl. Phys. A514 (1990) 1
5. P. Möller et al., At. Data and Nuc. Data Tab. 59 (1995) 185
6. B. Blank et al., Phys. Rev. Lett. 74 (1995) 4611
7. B. Sherill et al, this proceedings
8. I. Iben et al., Ap. J. Suppl. 100 (1995) 233
9. I. Lapidus et al., Ap. J. 433 (1994) 287