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International Journal of Mass Spectrometry 251 (2006) 293–299

International Journal of Mass Spectrometry

www.elsevier.com/locate/ijms

The importance of nuclear masses in the astrophysical rp-process

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Received 31 January 2006; received in revised form 6 February 2006; accepted 8 February 2006

Abstract

The importance of mass measurements for astrophysical capture processes in general, and for the rp-process in X-ray bursts in particular is discussed. A review of the current uncertainties in the effective lifetimes of the major waiting points ^{64}Ge, ^{68}Se, and ^{72}Kr demonstrates that despite of recent measurements uncertainties are still significant. It is found that mass measurements with an accuracy of the order of 10 keV or better are desirable, and that reaction rate uncertainties play a critical role as well.

Keywords: Nuclear masses; rp-Process; X-ray bursts

1. Introduction

Sequences of neutron and proton capture, interspersed with β-decays, play an important role in astrophysics. The slow- and rapid neutron capture processes (s- and r-process) are responsible for the synthesis of most of the elements beyond the iron group [1,2]. Slower proton captures generate much of the energy in Nova explosions and massive stars, while the rapid proton capture process (rp-process) powers type I X-ray bursts [3,4] and might also occur in a proton rich neutrino driven wind in core collapse supernovae [5,6].

The nature of such capture processes depends on the temperature and density conditions encountered in the stellar environment. At relatively low temperatures and densities capture reactions are typically much slower than β-decays. Captures can then only occur on stable or very long lived isotopes and the reaction paths proceed along the valley of stability. At somewhat higher temperatures and densities encountered mainly in explosive scenarios capture rates can become faster than β-decay rates and the sequence of reactions responsible for nucleosynthesis and energy generation moves towards unstable nuclei. At the most extreme conditions, nucleosynthesis paths are governed by partial (QSE, quasi nuclear statistical equilibrium) or full nuclear statistical equilibrium (NSE) as both, particle capture rates and the rates of their inverse photodisintegration processes triggered by high energy photons are fast. The nuclei favored in full NSE depend on the conditions, in particular electron fraction and entropy, but typically nucleosynthesis paths tend to shift to nuclei closer to stability, or, at the extreme involve only protons, neutrons, and alpha particles. The temperatures and densities during the astrophysical rapid neutron capture process (r-process) and rapid proton capture processes (rp-process) are just short of establishing NSE. These processes therefore proceed along some of the most exotic nuclei encountered in astrophysics. Nevertheless, at these extreme conditions some local equilibrium clusters do form—in the rp-process along isotonic chains as (p,γ)–(γ,p) equilibrium, and in the r-process along isotopic chains as (n,γ)–(γ,n) equilibrium. These equilibrium clusters tend to prevent the reaction paths from reaching or crossing the respective drip lines and determine the so called “waiting point” nucleus—the nucleus with the highest abundance in an equilibrium chain. Once equilibrium is established, the process has to wait for the waiting point nucleus to β-decay in order to proceed towards heavier nuclei.

In an isotonic or isotopic equilibrium the abundance ratio of two neighboring nuclei indexed by n and $n+1$ with increasing Z or N is simply given by the Saha equation:

$$\frac{Y_{n+1}}{Y_n} = \rho_{\mathrm{n}} \frac{G_{n+1}}{2G_n} \left(\frac{A_{n+1}}{A_n} \frac{2\pi\hbar^2}{m_{\mathrm{u}}kT} \right)^{3/2} \exp\left(\frac{S_{n+1}}{kT} \right) \tag{1}$$

where Y_n and Y_{n+1} are the abundances of an initial and final nucleus of a single proton or neutron capture reaction in the

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1387-3806/$ – see front matter © 2006 Published by Elsevier B.V.
doi:10.1016/j.ijms.2006.02.014

chain, T is the temperature, ρ_n the proton or neutron density, G the partition function, A the mass number, m_u the atomic mass unit, k the Boltzmann constant, and S is the proton or neutron separation energy, respectively. The maximum abundance in a chain and therefore the path of the process for a given density and temperature occurs at a fixed separation energy. Because of the exponential dependence on binding energy differences (S_{n+1} in Eq. (1)) nuclear masses are among the most important quantities for modeling the r- and rp-processes.

To which degree are equilibria along isotopic or isotonic chains realized in the r- or rp-process? Most but not all current r-process models, including models based on the neutron rich neutrino driven wind in core collapse supernovae, are based on a freezeout from some high temperature NSE or QSE state and therefore include an extended phase of more extended (n, γ)-(γ, n) equilibrium along isotopic chains. Before the fundamental problem of the site of the r-process is solved, it cannot be decided with certainty what the relevant nuclear processes are but to move the field forward it is critical to address the nuclear physics issues of the most promising models.

The situation for the rp-process in neutrino driven winds is similar with the system passing through a phase of (p,γ)–(γ,p) equilibrium prior to freezeout. On the other hand, the rp-process in X-ray bursts is characterized by a rapid heating phase (1–10 s) up to peak temperatures around 1.5–2 GK followed by a slower cooling phase (10–100 s) and freezeout. In X-ray bursts, extended (p,γ)–(γ,p) equilibrium in most isotonic chains is only established for the relatively short period during the peak of the burst when temperatures exceed about 1.2–1.3 GK. Even then, because of the relatively steep slope of the proton separation energy towards the proton drip line, there are still many important reactions where proton separation energies are too high and (γ,p) reactions are too slow to establish equilibrium. For example, for $N = 32$ the main rp-process flow proceeds via ^{64}Ge(p,γ)^{65}As(p,γ)^{66}Se with leakages through β-decays. The proton separation energy of ^{65}As is low (−0.36 MeV, see below) and therefore ^{65}As(γ,p) is fast, establishing (p,γ)–(γ,p) equilibrium during the entire phase of reaction flow during this region. On the other hand the proton separation energy of ^{66}Se is 2.4 MeV (see below). As we will show below, temperatures of more than 1.5 GK are required for ^{66}Se(γ,p) to establish a full (p,γ)–(γ,p) equilibrium between ^{65}As and ^{66}Se. Therefore, the rp-process in X-ray bursts proceeds through phases of partial (p,γ)–(γ,p) equilibrium, mostly between pairs of isotones near the proton drip line, and, depending on the peak temperatures reached in the particular X-ray burst model, a brief phase of complete (p,γ)–(γ,p) equilibrium at the highest temperatures.

Therefore, the rp-process in X-ray bursts is a rather complex process. The extent of equilibria is rapidly changing within seconds during the burst rise and within 10–100 s during the burst cooling. The reaction flows cannot be described simply with Eq. (1) and, as we will show below, proton capture rates play an important role during much of the rp-process. In addition, up to about $Z \sim 20$ (depending on the peak temperatures attained in a particular X-ray burst) (α,p) reactions can compete with proton capture chains and the respective branchings depend also on reaction rates. Nevertheless, masses are a critical part of the nuclear physics determining observables of X-ray bursts.

The sensitivity of r-process calculations to nuclear masses has been discussed extensively in the past (for example [2,7,8]). The rp-process in neutrino driven winds is a rather new concept with the added complication of an interplay with neutron induced reactions as neutrino interactions do create a sizeable neutron density [5,6]. Pruet et al.[6] point out that mass uncertainties directly affect the final abundances and that improved masses for neutron deficient isotopes, for example around ^{92}Ru, would be important to address the question of the contribution of this scenario to galactic nucleosynthesis. More work needs to be done to investigate in detail the nuclear physics sensitivities. In this paper we therefore concentrate on the role of masses in the rp-process in X-ray bursts. In contrast to the r-process, a significant number of masses along the rp-process have been detemined experimentally. Reviews of the relevant nuclear physics can be found in [9,4]. As all but a few rp-process nuclei have been observed in experiments, the proton drip line is roughly delineated by experimental constraints on the lifetime of nuclei. In addition, unknown masses can be predicted more reliably as one only needs to extrapolate a few mass units in most cases. This can be done using the extrapolation method of Audi et al. [10]. As the rp-process proceeds mostly beyond the $N = Z$ line one can also take advantage of isospin symmetry and calculate the masses of the most exotic rp-process nuclei from the better known masses of their mirrors. Brown et al. [11] have recently shown that mass shifts between isospin mirror nuclei can be calculated with an accuracy of 100 keV using a Skyrme Hartree-Fock model. However, this still requires accurate knowledge of the masses of the mirror nuclei that lie closer to stability. Despite of this progress, the typical theoretical mass uncertainties of many hundreds of keV are still not acceptable to reliably model X-ray bursts and to compare calculations with observations in a quantitative way. Mass measurements (together with reaction rate measurements) are therefore essential for a better understanding of the rp-process.

In Section 2 we begin by summarizing the astrophysical observables that drive the demand for improved nuclear physics in the rp-process. After discussing the importance of mass measurements for reaction rate calculations, we then focus in Section 3 on a series of recent precision mass measurements performed using ion traps. We explore the potential impact on rp-process calculations and the interplay of masses and reaction rates. In particular we show that even though tremendous progress has been made through recent experimental work, the question of the rp-process timescale for passing through the region of the major bottle-necks ^{64}Ge, ^{68}Se, and ^{72}Kr is still not resolved.

2. Masses in the rp-process

The rapid proton capture process powers type I X-ray bursts, which occur when a neutron star accretes hydrogen rich matter from a companion star in a binary system. See [12,13] for reviews of the astrophysical aspects and [4,9] for a recent review of the nuclear physics aspects. The observed burst light curves are sensitive to the underlying nuclear physics [11,14–16]. Nuclear physics is therefore needed to allow one to interpret burst observations in terms of system parameters such as the properties of the neutron star or the composition of the accreted matter. In addition, most of the nuclear burning ashes from X-ray bursts remains on the surface of the neutron star and gets incorporated into the crust by the ongoing accretion. The nuclear physics of X-ray bursts is therefore needed to accurately calculate the composition of the burst ashes and therefore the composition of the neutron star crust. A wide range of observable crust phenomena such as the rare superbursts [17] or the surface cooling behavior of the neutron star depend critically on composition [18]. This is particularly important as these phenomena could be used to constrain the properties of the neutron star if understood in a quantitative way. Finally, it has been shown recently that there is the possibility for some types of bursts to eject small but potentially observable amounts of burst ashes [19]. Nuclear physics is needed to accurately predict the observables and to match possible future observations with X-ray burst models.

Precision mass measurements are important for rp-process calculations for two reasons. First, as explained above, (p,γ)–(γ,p) equilibrium clusters form during the rp-process with the reaction flow largely determined by mass differences, i.e., proton separation energies. The mass sensitivity comes mainly from the $\exp(S_{n+1}/kT)$ term in Eq. (1). The second reason is the importance of accurate nuclear masses in the calculation of reaction rates, for example for proton capture. Most of the relevant nuclear reactions proceed through resonances, and the corresponding rate can be expressed as a sum over all resonances through [20]:

$$N_A\langle\sigma v\rangle = 1.540 \times 10^{11}(\mu T_9)^{-3/2} \times \sum_j \omega\gamma_j\, \mathrm{e}^{-E_j/(kT)}\,\mathrm{cm}^3\,\mathrm{s}^{-1}\,\mathrm{mole}^{-1} \quad (2)$$

with the resonance energy in the center of mass system E_j, the temperature in GK T_9 and the reduced mass of the entrance channel μ in amu. The resonance strengths $\omega\gamma_j$ are in MeV and can be calculated for proton capture as:

$$\omega\gamma_j = \frac{2J_j+1}{2(2J_T+1)}\frac{\Gamma_{pj}\Gamma_{\gamma j}}{\Gamma_{\text{total}\,j}} \quad (3)$$

where J_T is the target spin, and J_j, $\Gamma_{p\,j}$, $\Gamma_{\gamma\,j}$, $\Gamma_{\text{total}\,j}$ are spin, proton-decay width, γ-decay width, and total width of the compound nucleus state j.

Near the proton drip line level densities tend to be low limiting the applicability of more reliable statistical model calculations. Direct reaction rate measurements using low energy radioactive beams are extremely difficult due to limited beam intensities at existing radioactive beam facilities, and therefore Eq. (2) is often the only way to determine a reaction rate. The various ingredients, such as particle and radiative widths for the levels involved can be obtained from experiments or from shell model calculations [21,22]. However, as Eq. (2) shows, the reaction rate depends exponentially on the resonance energy, which is obtained from the excitation energy E_x of the resonant state using the reaction Q-value Q from $E_j = E_x - Q$. In addition, the proton width Γ_p in Eq. (3) includes the penetrability of the proton through the Coulomb barrier and depends therefore also exponentially on the resonance energy. Reaction rates calculated with Eq. (2) are therefore extremely sensitive to nuclear masses and excitation energies. Typically, resonance energies need to be known to better than 10 keV to keep the corresponding reaction rate uncertainty below about a factor of 2. This is far beyond the accuracy achievable with mass extrapolations for the Q-values, and shell model calculations for the excitation energies. The latter typically reach 100 keV accuracy in the rather well constrained sd-shell when the levels in mirror nuclei are accurately known [23].

Recently techniques have been developed to measure excitation energies of low lying states in very neutron deficient nuclei using radioactive beams. An example is the use of (p,d) transfer reactions in inverse kinematics using fast radioactive beams at the NSCL at Michigan State University [23,24]. In a first experiment excitation energies in ^{33}Ar needed for the calculation of the ^{32}Cl(p,γ)^{33}Ar reaction rates could be determined with accuracies of better than 10 keV. In addition, the mass of ^{33}Ar had been determined independently at ISOLTRAP [25] with an accuracy of 0.44 keV. Combining the mass and excitation energy measurements and using shell model calculations for all other level properties the reaction rate uncertainty could be reduced from a factor of about 10,000 to a factor of 3–6 [23]. Excitation energy measurements with fast radioactive beams are now possible for much of the rp-process up to about $A \sim 68$. However, these measurements need to be complemented with accurate measurements of ground state masses of better than 10 keV (1 keV accuracy is desirable) to be useful. As Fig. 1 shows masses are currently not known with sufficient accuracy for most of the rp-process path, even when experimental data are available. Further precision measurements of ground state masses using ion trap measurements together with measurements of excitation energies along the path of the rp-process are therefore needed.

3. The $A = 64$–72 rp-process bottlenecks

A particularly important part of the rp-process is the reaction flow through the region of the three major waiting points ^{64}Ge, ^{68}Se, and ^{72}Kr [4] with β-decay half-lives $T_{1/2}$ of 63.7, 35.5, and 17.16 s [26], respectively. Because these isotopes are located at the proton drip line, proton capture is hampered by (γ,p) reactions on the next, most likely proton unbound isotone. If the rp-process had to proceed via the β-decay of these waiting points, their combined β-decay lifetime $\tau_\beta = T_{1/2}/\ln 2$ of 168 s would represent a large impedance for the rp-process that would be comparable to typical burst timescales of 10–100 s. This would significantly slow down the rate of hydrogen burning and lead to extended burst tails. X-ray burst model calculations are therefore particularly sensitive to the question to which degree weak proton capture flows can reduce these lifetimes. This issue is at the heart of the question whether long burst timescales can be used as a signature of the rp-process and if one can use burst timescales to put quantitative constraints on the amount of hydrogen accreted. As discussed and demonstrated in several studies, X-ray burst lightcurves are directly sensitive to the

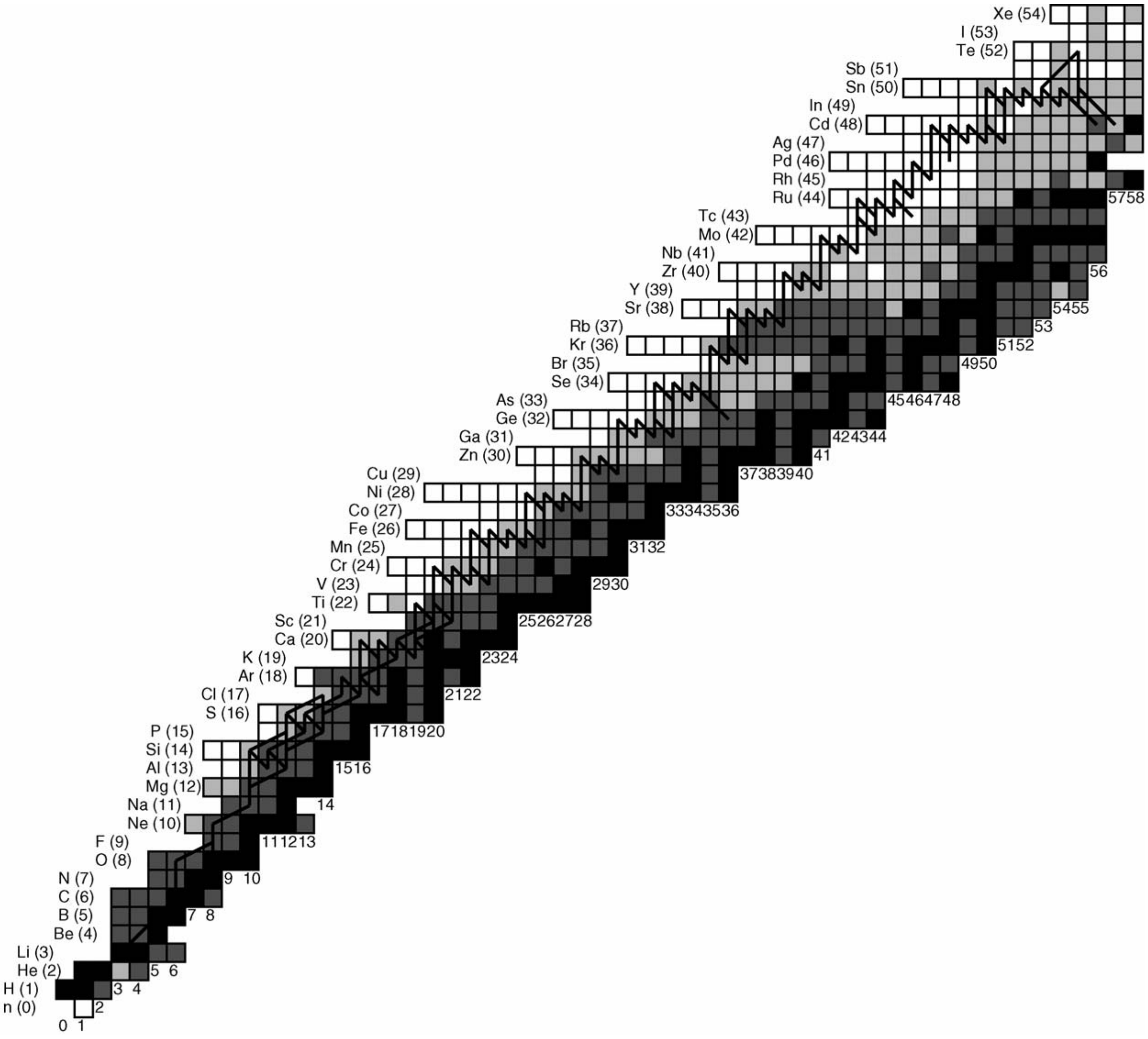

Fig. 1. The path of the rp-process (from [15]) on the chart of nuclides. Stable nuclei are black, nuclei with experimentally known masses are grey–dark grey for uncertainties of less then 10 keV, light grey for larger uncertainties. For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.

effective lifetimes of the waiting points ^{64}Ge, ^{68}Se, and ^{72}Kr [4,11,14–16].

The nuclear physics determining the effective rp-process lifetime of major waiting points has been discussed extensively in Schatz et al. [4]. In the following we discuss in detail the situation at the ^{64}Ge waiting point. Analogeous processes occur at ^{68}Se and ^{72}Kr. The proton capture flow on ^{64}Ge proceeds via a so called 2p-capture reaction. Current mass predictions (see below) predict ^{65}As to be slightly unbound with a proton separation energy of −0.36 MeV. The Coulomb-barrier is sufficient to suppress spontaneous proton-decay so that ^{65}As decays under terrestrial conditions by β-decay in agreement with experimental evidence [26]. The low proton separation energy leads to an establishment of a (p,γ)–(γ,p) equilibrium between ^{64}Ge and ^{65}As at all times when there is reaction flow in this mass region. Also, because of the low proton separation energy the equilibrium abundance of ^{65}As is very low. Nevertheless, proton capture on ^{65}As can lead to a significant 2p-capture flow that can reduce the lifetime of ^{64}Ge during an X-ray burst. At X-ray burst peak conditions ^{64}Ge, ^{65}As, and ^{66}Se are in (p,γ)–(γ,p) equilibrium. The net 2p-capture flow through this isotonic chain and therefore the effective lifetime of ^{64}Ge is then determined by the leakage out of the equilibrium via the β-decay of ^{66}Se. The most critical quantities to determine the 2p-capture rate and the effective lifetime of ^{64}Ge for a given temperature and proton density are therefore the β-decay half-lives of ^{64}Ge and ^{66}Se, the proton separation energies of ^{65}As and ^{66}Se, and the proton capture rate on ^{65}As. Accordingly, the β-decay half-lives of ^{68}Se, ^{70}Kr, ^{72}Kr, ^{74}Sr, the proton separation energies of ^{69}Br, ^{70}Kr, ^{73}Rb, ^{74}Sr, and the proton capture rates on ^{69}Br and ^{73}Rb are of importance for the waiting points at ^{68}Se and ^{72}Kr, respectively.

While the β-decay half-lives of the important nuclei around these major waiting points have been known in most cases for some time [26,27], it has recently become possible to also perform precision mass measurements using ion traps in this mass region. Of particular importance are recent mass measurements

Table 1
Proton separation energies S_p and uncertainties in MeV used for this study

$S_p(^{65}\mathrm{As}) = -0.36 \pm 0.15$
$S_p(^{69}\mathrm{Br}) = -0.81 \pm 0.10$
$S_p(^{73}\mathrm{Rb}) = -0.70 \pm 0.10$
$S_p(^{66}\mathrm{Se}) = 2.43 \pm 0.18$
$S_p(^{70}\mathrm{Kr}) = 2.58 \pm 0.16$
$S_p(^{74}\mathrm{Sr}) = 2.20 \pm 0.14$

The masses for ^{64}Ge, ^{68}Se, and ^{72}Kr are from recent experiments [28,30], with the mass of ^{64}Ge being taken from a preliminary analysis (see footnote 1). The remaining masses were obtained from the isospin mirrors using the Coulomb shifts from [11]. The masses of the mirror nuclei ^{73}Kr and ^{74}Kr are from [30], for all others from [10].

of ^{64}Ge [1] and ^{68}Se [28] using the Canadian Penning Trap at ANL (the mass of ^{68}Se had also been determined independently using the β-endpoint technique [29]) and the mass measurements of $^{72-74}$Kr at ISOLTRAP [30]. In addition, Skyrme Hartree-Fock calculations allow now the calculation of Coulomb mass shifts between mirror nuclei with an estimated accuracy of 100 keV [11]. While mass measurements on ^{65}As, ^{66}Se, ^{69}Br, ^{70}Kr, ^{73}Rb, and ^{74}Sr have not been feasible so far, their isospin mirrors are within reach for ion trap mass measurements. This has already been demonstrated for ^{73}Kr and ^{74}Kr, which are the mirrors to ^{73}Rb and ^{74}Sr [30]. Similar measurements on ^{65}Ge, ^{66}Ge, ^{69}Se and ^{70}Se would be desirable. If an accuracy of 10 keV or better can be reached, these mass measurements can be combined with Coulomb shift calculations to provide mass predictions that are accurate to about 100 keV.

We use the currently available mass data on rp-process nuclei and their mirrors together with Coulomb shift calculations [11] to analyze the current uncertainties in the effective lifetimes τ_{eff} of ^{64}Ge, ^{68}Se, and ^{72}Kr with $\tau_{\mathrm{eff}} = 1/(\tau_{\beta}^{-1} + \tau_{2p}^{-1})$, τ_{β} being the β-decay lifetime, and τ_{2p} being the lifetime against 2p-capture. The proton separation energies used for this study are listed in Table 1 with their uncertainties. We follow here the method outlined in Rodriguez et al. [30] for the case of ^{72}Kr. For each waiting point we performed a small network calculation to determine the effective lifetime against proton capture and β-decay as a function of temperature and proton density. The network included the proton captures on the waiting point (Z, A) and the following isotone, their inverse (γ,p) reaction rates as well as the β-decay rates of the three nuclei involved. β-Decay rates were taken from nubase [26] when available. For ^{74}Sr we used an estimate of 50 ms [27]. For the even–even nuclei no changes in half-lives with temperature or density compared to terrestrial values are expected for X-ray burst conditions [27]. As mentioned below the calculations are insensitive to the β-decay rates of the odd Z nuclei. Proton capture rates were taken from the statistical model NON-SMOKER [31]. An upper and a lower limit within the mass uncertainties was calculated by assuming the upper one-sigma limits or the lower one-sigma limits for both proton capture Q-values respectively. To explore the impact of reaction rates, we in addition increased or decreased the proton capture rate on the $(Z, N+1)$ isotone following the waiting point by a factor of 100 up or down. Such uncertainties of four orders of magnitude are typical for reaction rates that are dominated by only a few resonances, and where excitation energies are uncertain to 100 keV [23]. This is a reasonable range to explore, as here already the reaction Q-values are uncertain by at least 100 keV. However, it is not an accurate estimate of the uncertainty of statistical model calculations in the cases under consideration, which is difficult to obtain given the lack of experimental and theoretical information. We neglect uncertainties in the β-decay rates. While most β-decay rates are known with sufficient precision, the partial β-decay half-lives of ^{69}Br, ^{73}Rb and ^{74}Sr are not known experimentally. Test calculations showed that the results are insensitive to the half-lives of ^{69}Br and ^{73}Rb because their equilibrium abundances are so low and proton capture tends to be faster. Varying the ^{74}Sr half-life between 10 ms and 100 ms did change the ^{72}Kr effective lifetime by about 10%.

The resulting values and bounds for the effective lifetimes of ^{64}Ge, ^{68}Se, and ^{72}Kr for a mass density of 10^6 g/cm^3 and a proton mass fraction of 0.7 are shown in Figs. 2 and 3 as functions of temperature. At low temperatures proton captures are ineffective. The lifetime is then set by the β-decay lifetime and is independent of masses and reaction rates. At the highest temperatures, photodisintegration effectively prevents any proton capture flow by driving the abundance distribution of the

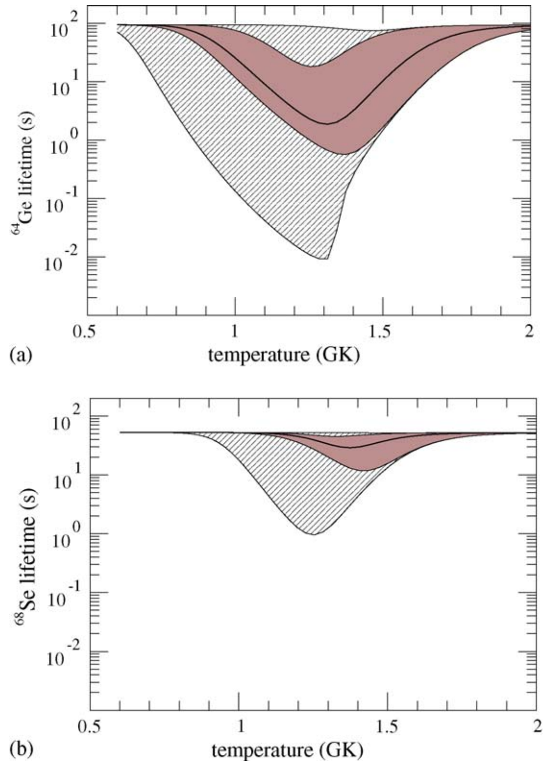

Fig. 2. The effective lifetime of ^{64}Ge (a) and ^{68}Se (b) during rp-process conditions as a function of temperature taking into acocunt destruction by β-decay and proton capture. The grey area denotes the uncertainty due to masses. The hatched area delineates the uncertainty when considering an additional error of a factor of 100 up or down for the ^{65}As(p,γ)^{66}Se reaction rate in the ^{64}Ge case and for the ^{69}Br(p,γ)^{70}Kr rate in the ^{68}Se case.

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[1] J.A. Clark, et al., Proceedings of the Fourth International Conference on Exotic Nuclei and Atomic Masses, 2004, p. 59, and private communication, value from preliminary analysis.

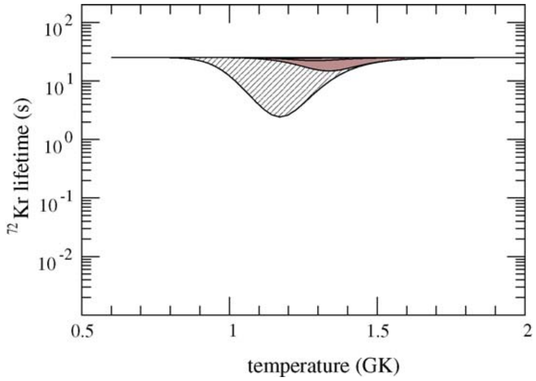

Fig. 3. Same as Fig. 2 but for ^{72}Kr. The reaction rate varied is the ^{73}Rb(p,γ)^{74}Sr rate. This is similar to Fig. 2 in [30].

(p,γ)–(γ,p) equilibrium towards the waiting point. Again, the effective lifetime becomes dominated by the β-decay lifetime of the waiting point nucleus (Z, N). The sensitivity of the lifetime to the proton capture rate on the isotone following the waiting point $(Z + 1, N)$ indicates the degree to which equilibrium is established. The onset of the rate sensitivity at the lowest temperatures indicates the establishment of a (p,γ)–(γ,p) equilibrium between the (N, Z) and $(N, Z + 1)$ nuclei. As one can see, such an equilibrium is always established for the temperature range of interest here owing to the very low separation energy of the $(N, Z + 1)$ nuclei. The disappearance of the reaction rate sensitivity at higher temperatures indicates the establishment of full (p,γ)–(γ,p) equilibrium between the (Z, N), $(Z + 1, N)$ and $(Z + 2, N)$ nuclei. In that case, the reaction flows become insensitive to proton capture reaction rates.

Clearly, in the case of ^{72}Kr the precision mass measurements of ^{72}Kr and the mirrors to the isotones ^{73}Rb and ^{74}Sr, ^{73}Kr and ^{74}Kr, with uncertainties of 8 keV or less have drastically reduced mass related lifetime uncertainties to less than a factor of 2. Still, the remaining $\approx 50\%$ uncertainty at 1.3 GK might be relevant for precision tests of X-ray burst models, depending on the lifetimes of the preceding waiting points. A further reduction of the uncertainty is however only possible through a measurement of the mass of ^{73}Rb, a proton unbound nucleus with a lifetime of less than 30 ns [26]. Transfer or proton removal reactions might be a possibility to achieve this. Reaction rate related uncertainties still allow for the possibility to reduce the effective ^{72}Kr lifetime significantly below the β-decay lifetime.

For ^{68}Se and ^{64}Ge the situation is worse owing to the larger mass uncertainties and the higher proton separation energies, which facilitate 2p-captures and increase the mass sensitivity of the lifetime. Clearly in these cases the current mass uncertainties are still too large to allow for reliable X-ray burst simulations. For example, at 1.4 GK the ^{64}Ge lifetime ranges from 0.6 to 40 s depending on the adopted mass. This is particularly relevant as this is the first of the major waiting points. It is important to note that both, the proton separation energy of ^{65}As and the proton separation energy of ^{66}Se are needed. The uncertainty in the proton separation energy of ^{65}As dominates the uncertainty in the lifetime up to about 1.3 GK. The proton separation energy of ^{66}Se determines at which temperature the ^{66}Se(γ,p) rate kicks in causing the rise of the lifetime with temperature beyond about 1.3 GK. Beyond 1.3 GK the uncertainties in the proton separation energies of ^{65}As and of ^{66}Se contribute with roughly equal proportions to the lifetime uncertainty.

Clearly the current uncertainties in the proton separation energies (see Table 1) need to be reduced further by experiments. For the proton separation energy of ^{65}As, the 100 keV mass uncertainty of the mirror nucleus ^{65}Ge contributes significantly. A measurement of the ^{65}Ge mass with an accuracy of at least about 30 keV would therefore already reduce the lifetime uncertainty of the ^{64}Ge waiting point. Such a measurement has been performed recently with the ion trap at Michigan State University's LEBIT facility [2]. An improved ^{70}Se mass (current uncertainty is 62 keV) would slighly improve the calculated ^{70}Kr mass needed for the ^{70}Kr proton separation energy. Such a measurement should be possible at existing facilities.

However, as Fig. 2 shows for the case of ^{68}Se, an accuracy level of the order of 100 keV is not sufficient for reliable rp-process calculations. At least for the ^{64}Ge and ^{68}Se waiting points a mass accuracy of the order of 10 keV would be desirable for the relevant nuclei. While there is room for slight improvements in the mass measurements of ^{64}Ge (30 keV uncertainty) and ^{68}Se (20 keV uncertainty), this will not make much difference until the 100 keV error in the Coulomb Shift calculations for the masses of ^{65}As, ^{66}Se, ^{69}Br, and ^{70}Kr is addressed. ^{65}As, ^{66}Se and ^{70}Kr are β-emitters and sufficiently accurate mass measurements at ion traps might become feasible when beam intensities at radioactive beam facilities can be improved. The mass of proton decaying ^{69}Br can only be determined through reactions populating the short-lived ground state. β-decay of ^{69}Kr or proton removal reactions are possibilities and might be feasible at existing radioactive beam facilities. In parallel, improved theoretical estimates of the proton capture rates on ^{65}As and ^{69}Br would be helpful, as these could reduce, or increase, the sensitivities to nuclear masses (see Fig. 2).

4. Conclusions

Masses play a critical role in the r- and rp-processes. For the rp-process in X-ray bursts, masses in the vicinity of the major waiting points ^{64}Ge, ^{68}Se, and ^{72}Kr are particularly important. While mass uncertainties have been reduced significantly through experimental and theoretical progress, they are still too large to reliably determine the effective lifetimes of these waiting points in the rp-process. Mass related lifetime uncertainties for ^{64}Ge, ^{68}Se, and ^{72}Kr still amount to up to factors of 60, 4, and 1.7 respectively with the combined effective lifetime of all three waiting points at 1.4 GK ranging from 29 to 108 s. In general, mass accuracies of the order of 10 keV are needed to sufficiently constrain 2p-capture flows. While some of the relevant measurements should be feasible at existing facilities, others will require considerable advances.

As we have also shown, all lifetimes are sensitive to the proton capture rates on ^{65}As, ^{69}Br, and ^{73}Rb. Without reliable estimates

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[2] G. Bollen, et al., private communication, 2006.

for these reaction rates (upper limits would already be helpful) the question to which degree the rp-process reaction flow is impeded by the waiting points ^{64}Ge, ^{68}Se, and ^{72}Kr cannot be answered reliably. For example, within all the uncertainties the effective lifetime of ^{64}Ge can still range from 10 ms to the full β-decay lifetime of 92 s. In the former case, ^{64}Ge would not delay the rp-process at all, while in the latter case it would be the singly most important waiting point imposing a delay of the order of the burst timescale. Direct measurements of these reaction rates are difficult, or, in the case of the proton captures on ^{73}Rb or ^{69}Br, impossible due to the sub microsecond lifetime of the target nuclei. However, decay and transfer reactions clarifying the structure of the final nuclei, or Coulomb breakup, might be possibilities in the future. Until then, a better theoretical description and further experimental clarification of the structure of the mirror nuclei would be helpful.

Acknowledgements

Support through NSF grants PHY 0110253 and PHY 02 16783 (Joint Institute for Nuclear Astrophysics) is acknowledged. We thank J.A. Clark for providing his preliminary results for the mass of ^{64}Ge, T. Rauscher for providing the NON-SMOKER rates, and F.-K. Thielemann for providing the reaction network solver.

References

[1] F. Käppeler, Prog. Part. Nucl. Phys. 43 (1999) 419.
[2] J.J. Cowan, F.-K. Thielemann, J.W. Truran, Phys. Rep. 208 (1991) 267.
[3] R.K. Wallace, S.E. Woosley, Ap. J. Suppl. 45 (1981) 389.
[4] H. Schatz, et al., Phys. Rep. 294 (1998) 167.
[5] C. Fröhlich, et al., Ap. J. 637 (2006) 415.
[6] J. Pruet, et al., Ap. J. 623 (2005) 325, and astro-ph/0511194.
[7] B. Pfeiffer, et al., Nucl. Phys. A 693 (2001) 282.
[8] S. Wanajo, S. Goriely, M. Samyn, N. Itoh, Ap. J. 606 (2004) 1057.
[9] H. Schatz, K.E. Rehm, Nucl. Phys. A., in press.
[10] G. Audi, A.H. Wapstra, C. Thibault, Nucl. Phys. A 729 (2003) 129.
[11] B.A. Brown, R.R.C. Clement, H. Schatz, A. Volya, W.A. Richter, Phys. Rev. C 65 (2002) 045802.
[12] D. Psaltis, astro-ph/0410536, 2004.
[13] T.E. Strohmayer, L. Bildsten, in: W.H.G. Lewin, M. van der Klies (Eds.), Compact Stellar X-ray Sources, Cambridge University Press, Cambridge, astro-ph/0301544, 2003.
[14] O. Koike, et al., Astron. Astrophys. 342 (1999) 464.
[15] H. Schatz, et al., Phys. Rev. Lett. 86 (2001) 3471.
[16] S.E. Woosley, et al., Ap. J. Suppl. 151 (2004) 75.
[17] J.M.M. in't Zandt et al. astro-ph/0407087, 2004.
[18] E.F. Brown, Ap. J. 614 (2004) 57.
[19] N.N. Weinberg, L. Bildsten, H. Schatz, Ap. J. astro-ph/0511247, in press.
[20] W.A. Fowler, F. Hoyle, Ap. J. Suppl. 9 (1964) 201.
[21] H. Herndl, et al., Phys. Rev. C 52 (1995) 1078.
[22] J.L. Fisker, et al., Atom. Data Nucl. Data Tab. 79 (2001) 241.
[23] H. Schatz, et al., Phys. Rev. C 72 (2005) 065804.
[24] R.R.C. Clement, et al., Phys. Rev. Lett. 92 (2004) 172502.
[25] K. Blaum, et al., Phys. Rev. Lett. 91 (2003) 26.
[26] G. Audi, et al., Nucl. Phys. A 729 (2003) 3.
[27] J. Pruet, G.M. Fuller, Astrop. J. Suppl. 149 (2003) 189.
[28] J.A. Clark, et al., Phys. Rev. Lett. 92 (2004) 192501.
[29] A. Wöhr, et al., Nucl. Phys. A 742 (2004) 349.
[30] D. Rodriguez, et al., Phys. Rev. Lett. 93 (2004) 161104.
[31] T. Rauscher, F.-K. Thielemann, Atom. Data Nucl. Data Tab. 75 (2000) 1.