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The importance of nuclear masses in the astrophysical rp-process

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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:

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

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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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]. Nu-