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Explosive processes in nucleosynthesis

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Abstract. There are many explosive processes in nucleosynthesis: big bang nucleosynthesis, the rp-process, the γ-process, the ν-process, and the r-process. However, I will discuss just the rp-process and the r-process in detail, primarily because both seem to have been very active research areas of late, and because they have great potential for studies with radioactive nuclear beams. I will also discuss briefly the γ-process because of its inevitability in conjunction with the rp-process.

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1 Introduction

Recent advances in our understanding of nucleosynthesis feature processes at both extremes of the periodic chart of the nuclides. The r-process, one possible site for which is the hot neutrino bubble that results from collapse of a massive star to a neutron star, passes through neutron-rich nuclides that lie roughly 20 neutrons to the neutron-rich side of stability, and reach the heaviest nuclei that Nature can produce. The path of the high-temperature rp-process, which can occur in a hydrogen-rich high-temperature environment produced by accretion onto a neutron star or black hole, passes through the most proton-rich nuclei that exist in Nature.

The challenge for the nuclear astrophysicist is to describe the nuclei from the neutron drip line to the proton drip line, and reaching to the heaviest nuclei that Nature can synthesize, so that the processes that stars utilize to synthesize the elements can be understood.

2 The r-process of nucleosynthesis

Several distinctive features appear to be essential for the r-process [1]. It must produce the abundance peaks observed at mass 130 and 195 u, and it must synthesize all the nuclides heavier than ^{209}Bi. Also, it must not depend on pre-existing seed nuclei, *i.e.*, it must be "primary". The first two requirements come from considerations of nuclear astrophysics. The third comes from astronomical observations of low-metallicity stars, which show [2] that the r-process produces precisely the same ratio of abundances of nuclides heavier than 130 u in the earliest stars in our Galaxy as in those that have been seeded by several generations of preceding stars. This could happen only if the r-process is somehow independent of its pre-existing seed nuclei.

One scenario that seems consistent with this observation results from "alpha-rich freezeout", thought to originate in the high initial temperature, 40 billion K, that occurs at the collapse of a massive star. At such a temperature all pre-existing nuclei are destroyed. Then as the high temperature decreases, nuclei are assembled in nuclear statistical equilibrium. NSE depends exponentially on the nuclear binding energies, so tends to make stable nuclei. However, it also depends on neutron density. Nonetheless, if the entropy is sufficiently high, alpha-rich freezeout can synthesize nuclei up to 100 u; these then become the seeds for the subsequent r-process. Alpha-rich freezeout probably takes place in a fraction of a second, the r-process in about 10 seconds. The conditions required for a successful NSE-r-process have been studied in detail by Hoffman *et al.* [3].

Recent developments in understanding the r-process involve experimental and theoretical work both on the nuclei through which it passes and on neutrino astrophysics. The r-process synthesizes heavier nuclei by adding neutrons to lighter nuclear seeds with occasional β-decays interspersed. Since the r-process is thought to proceed along a path that is roughly 20 neutrons to the neutron-rich side of stability, all the nuclei along its path are unstable, usually with very short half-lives. As these nuclei increase in mass, they occasionally reach "waiting-point nuclei" at which further progression is inhibited by either a relatively long half-life or an inability to capture another neutron. Both occur at the closed-neutron-shell nuclei. Since abundance will build up at the waiting-point nuclei in accordance with their half-lives, the half-lives determine the abundances of the progenitors and, hence, of the resulting r-process nuclei when the conditions of the r-process end and the progenitors decay back to stability. Thus, studies of the properties of the closed-neutron-shell nuclides are crucial to our understanding of the r-process. Numerous measurements of both the structure and half-lives of such nuclides have been made by the ISOLDE group (see, *e.g.*, [4], and references therein) of nuclides around the mass 130 u waiting point. Measurements of this type include ^{130}Cd [5], which lies fourteen neutrons beyond the most neutron-rich stable cadmium isotope, and is thought to be one of the waiting-point nuclides on the r-process path.

However, there are other aspects of nuclei that can influence the r-process abundances. These include shell quenching in the very neutron-rich nuclides along the r-process path. Since the abundance peaks are thought to occur at the neutron closed shells, quenching of the shell closures [6] will certainly affect the abundances and locations of the r-process peaks. However, only measurements of the nuclear structure of the nuclides involved will determine the real impact of shell quenching on the r-process; such studies should keep nuclear experimentalists busy for many years. Another effect involves the β-decays of the excited states of the nuclei along the r-process path. These are not normally included in r-process simulations, but the excited states would be expected to decay with shorter half-lives than the ground states, and they would be expected to be populated to some extent in the high-temperature environment in which the r-process is thought to occur. One group [7] has rewritten the "gross theory of β-decay" [8,9] to include shell effects, which then allows the calculation of excited-state decay rates. These decays do appear to be important to the r-process, increasing the predicted abundances at the mass 195 u peak, population of which seems to be the main difficulty in r-process simulations, by as much as an order of magnitude.

Experimental work on understanding alpha-rich freezeout, which is thought to precede the r-process, has also involved studies of unstable nuclei. One group [10] is studying reactions that involve ^{44}Ti, and can affect the amount of it that is produced in a core collapse supernova. ^{44}Ti is sufficiently long-lived that it can be expelled in a supernova to provide a diagnostic of the core-collapse process; it has been observed in the nebula of a supernova [11] by a gamma-ray observatory. This observation produced a crisis. Two values of the half-life of ^{44}Ti that had been measured until a few years ago had produced values of either about 45 years or about 60 years. The amount of ^{44}Ti produced in the Cas A supernova could be inferred from the amount observed in the Cas A nebula, extrapolated back to the time at which the Cas A supernova occurred using the half-life. The longer one gave reasonable agreement between theory and experiment of the amount of ^{44}Ti observed, whereas the shorter one produced a serious conflict. Several remeasurements [12–14] of the half-life confirmed the longer value, averting the crisis, but only marginally. Thus a recent study [15] has considered the possibility that density nonuniformities might allow the ^{44}Ti to remain highly ionized for a long time after being produced. Since ^{44}Ti decays by electron capture, this could greatly extend its effective half-life.

Another aspect of recent r-process research has involved the effect of neutrinos on it. The neutrinos apparently carry away 99% of the energy produced in a core-collapse supernova. They also can provide a huge assist to the r-process, as they can, through (ν_e, e^-) reactions, simulate β-decays. Several of the mass 130 u progenitor nuclei have half-lives that are comparable to, or longer than, the time during which the r-process operates, so these neutrino induced reactions can greatly expedite the flow of nuclei past that point, and on to the mass 195 u progenitor nuclides. The r-process must occur in an extremely neutron-rich region to produce the many neutron captures needed to produce heavy nuclei. However, the same neutrinos that can expedite the r-process could also convert many of the neutrons that exist in the region just outside the core of the star to protons, which would kill the r-process [16]. Of course, neutrinos are known, as a result of observations from Super-Kamiokande [17] and SNO [18] to oscillate. Furthermore, these oscillations can depend on the density of the matter through which the neutrinos pass. It has been observed that these oscillations may be essential in the core of a star in order to allow the r-process to occur at all [19,20]. Terrestrial experiments on neutrinos can determine some of their characteristics, but observations of the neutrinos from a supernova [21] would greatly expand our knowledge of their properties.

3 The rp-process, the γ-process, and the (rp)^2-process

Progress has also been made in understanding the rp-process, both in its low-temperature form, as might occur in matter accreted onto a white dwarf, and in its high-temperature form, which might occur in the accreted matter as it approaches the surface of the neutron star or black hole. The low-temperature site would be expected to produce a nova. The nuclear reactions that characterize it were discussed in a review article by Champagne and Wiescher [22]. These reactions will certainly be the subjects of much experimental effort in the next few years.

Although I will not discuss the low-temperature rp-process much in this presentation, some of its features are important also to the high-temperature process. Specifically, waiting points can occur as the protons drive the seed nuclei to the proton drip line in cases where another proton capture produces a nucleus that will proton decay. Then a β-decay is essential for the rp-process to continue past that point. Another type of waiting point, however, can occur if the proton capture produces a nucleus that is stable to proton emission, but which has only a small binding energy. Then the hot photon bath that accompanies the elevated temperature of the rp-process is likely to produce a (γ,p) reaction, again halting the rp-process until a β-decay can occur.

In the present paper, though, I will concentrate on the high-temperature rp-process. The accretion onto the neutron star or black hole will eventually produce X-ray bursts, which have been observed in X-ray satellites. Understanding the energy and nucleosynthesis produced by these events are the twin goals of the research being conducted. The nucleosynthesis is thought to occur in the layers that lie just above the surface of the neutron star (see, *e.g.*, ref. [23]), and are separated by distances of order ten meters [24]. The infalling matter heats up as it falls into the deep gravitational well of the neutron star, achieving a temperature of up to 1.5 billion K. The protons that exist in the infalling matter are quickly captured on the (abundant) CNO seed nuclei to create heavier seeds for the high-mass rp-process. Occasional β-decays keep the nuclei along the rp-process within the proton drip line, but occasional waiting-point nuclei occur at the drip line. The rp-process slows at waiting-point nuclei, just as the r-process does; these become the progenitors of its abundance peaks. A particularly challenging region for the rp-process lies in the proton-rich isotopes of Mo and Ru. They are "p-nuclei" [25, 26] which cannot be made by the two processes of nucleosynthesis that synthesize most of the nuclides heavier than iron. Both of these processes (one is the r-process) involve neutron captures and β-decays, so operate at or beyond the neutron-rich edge of the valley of stability. Thus, they are blocked from synthesizing the p-nuclei by stable nuclei. The p-nuclei are apparently only made by complex processes, so generally have abundances less than 1% of that of their respective element. The Mo and Ru p-nuclides, however, have atypically large abundances. Only recently has any nucleosynthesis model come close to predicting successfully the abundances of the Mo and Ru p-nuclides.

Note that many high-energy photons will exist in the high-temperature bath in which the rp-process occurs. These would produce photonuclear reactions on the heavy nuclides that exist in that region. These reactions are at the heart of the "γ-process", by which pre-existing seed nuclei are processed into lighter nuclides, apparently synthesizing nearly all of the heavy p-nuclei [27]. However, in scenarios involving the rp-process, the photonuclear reactions are very important; an equilibrium is established between (p,γ) and (γ,p) reactions at many of the nuclei. Thus the γ-process is *inevitable* in regions in which the rp-process occurs; its reactions must be included in any description of the rp-process, especially at high temperatures.

One study [28] pushed the density, temperature, and processing time of the rp-process to their plausible extremes. The effects were dramatic; large abundance enhancements were achieved for the Mo and Ru p-nuclides. However, some questions still exist. First, how does one move the nuclei produced out of the gravitational field of the neutron star and into the interstellar medium? Second, can the fact that some of the non-p-nuclides synthesized in large abundance be reconciled with the fact that they are also made in other processes of nucleosynthesis, thereby possibly overproducing these isotopes? Third, do events occur in Nature that have the long processing times required of this model of the high-temperature rp-process? With respect to the first issue, a tiny fraction of the material synthesized would be expected to escape from the neutron star, and the production of the Mo and Ru p-nuclei is enormous in this production site. The amount emitted into the interstellar medium is a product of the overproduction factor (the ratio of the isotope of interest to hydrogen compared to that same ratio in the cosmic abundances), the frequency of occurrence, and the fraction that escapes from the gravitational field of the neutron star or black hole. If the overproduction factor is large enough, this can explain the desired abundance. The second issue could be troublesome, but it also may go away when all the data needed to describe the reactions and half-lives of the nuclei involved in this processing scenario are known. These are nuclei that in some cases have never been produced in the laboratory (although Nature seems to have no difficulty doing so!). The answer to the third question is apparently that such events do occur, but their number is not a large fraction of the X-ray bursts observed. One interesting feature of this form of the rp-process is that it has a termination point. The nuclei just beyond ^{100}Sn are known to decay by α-particle emission. This means that, when successive proton captures reach these nuclides, they will emit an α-particle, producing a cycle, and prohibiting progression beyond them [29]. Thus abundance will build up in those nuclei, the progenitors of the stable nuclei around ^{104}Pd. This might produce an observable signature in, *e.g.*, X-ray emission of these nuclei, assuming they could be emitted from the neutron star.

A variant of this rp-process would exist if rp-processing could occur in many successive bursts; this has been dubbed the (rp)^2-process [30]. Its path would differ somewhat from that of the rp-process, as the short processing times that it admits would not push the pre-existing nuclides as close to the proton drip line as would the rp-process. The (rp)^2-process could also circumvent the mass 104 termination point of the high-temperature rp-process, as the nuclei that decay back to stability after each processing burst would progress beyond any waiting points imposed by the previous processing pulse.

4 Conclusions

The nuclei through which both the r- and rp-processes pass are so far from stability that they may be very difficult to produce in the laboratory. Future work using radioactive beams will produce information that will be crucial to our understanding of these processes. And future theoretical work that folds in these data will almost certainly make new testable predictions.

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