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SOME NUCLEAR DATA NEEDS IN ASTROPHYSICS

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Abstract In this paper we discuss a number of astrophysical environments and how improved nuclear data could facilitate a better understanding of them. One area of interest includes proton and alpha-particle reactions with unstable nuclei which are necessary for understanding the nucleosynthesis and energy generation in hot hydrogen-burning environments. Efforts underway at LLNL and elsewhere to develop the technology for the measurement of these reaction rates are discussed. Heavy-element nucleosynthesis in the late stages of red-giant stars and supernovae requires a complete network of neutron capture rates and beta-decay rates for nuclei near and far from stability. Experimental and theoretical efforts at LLNL to supply the input data and to model the nucleosynthetic environments will be outlined. Suggestions are made as to which nuclear data are most critical for the various scenarios.

INTRODUCTION

Even after several decades of research¹ into the mechanisms by which the elements are synthesized in stars, it is still often true that the degree to which an astrophysical environment can be understood is limited by the degree to which the underlying microscopic input nuclear physics data have been measured and understood. As new and more exotic astronomical environments have been discovered and modelled (and as observations and models for more familiar objects have been refined) the needs for more and better nuclear data have increased. In this brief overview, we discuss a few of the current nuclear data needs in astrophysics and some of the efforts underway to meet them. Many of the required input data involve reaction rates and decay rates for unstable nuclear states. Obtaining this information poses some challenging problems to experimentalists and theorists, but

at least some of these data, which have previously appeared unobtainable, are beginning to come within reach.

We begin with a discussion of the exotic environments for hot hydrogen burning and some of the experimental and theoretical efforts to obtain the desired nuclear data. Then we turn to a discussion of the poorly understood mechanisms for neutron-capture nucleosynthesis and efforts to supply the desired capture rates and beta-decay rates. In both of these discussions we try to give some picture of the current needs and the prospects for fulfilling these needs in the not too distant future.

HOT HYDROGEN BURNING IN HEAVENLY ENVIRONS

Since the landmark work of Wallace and Woosley² it has become more clear that hydrogen burning may occur at temperatures far in excess of the temperatures ($10^6 < T < 10^8 \text{K}$) associated with the main-sequence evolution of normal stars for a host of astrophysical environments (see Fig. 1). In such environments the need for charged-particle reaction data for unstable nuclei becomes particularly important.

Almost any time there is thermonuclear hydrogen burning, there is a possibility for proton reactions on unstable nuclei. Well known examples are the ${}^7\text{Be}(p,\gamma){}^8\text{B}$ reaction in the sun (which is a particularly important link in the chain of reactions leading to the production of solar neutrinos detectable in the ${}^{37}\text{Cl}$ experiment³), the ${}^{22}\text{Na}(p,\gamma){}^{23}\text{Mg}$ reaction in the Ne-Na cycle, and the reactions of ${}^{26}\text{Al}$ in the Mg-Al cycle. When the temperatures are high, a few other reaction rates also become important. For $T \gtrsim 2 \times 10^8 \text{K}$ the weighting point for the normal hydrogen-burning CNO cycle shifts⁴ from ${}^{14}\text{N}$ to ${}^{13}\text{N}$, and then, via the ${}^{13}\text{N}(p,\gamma){}^{14}\text{O}$ reaction, shifts to the production of ${}^{14}\text{O}$ and ${}^{15}\text{O}$. This is the hot (beta-limited) CNO cycle², which is particularly significant in the evolution of supermassive ($M > 10^4 M_\odot$) stars⁵. This hot hydrogen-burning scenario may also come into play on accreting white dwarfs² and in the formation of x-ray bursts from accreting neutron stars^{6,7}.

As the temperature and density continue to increase, the ${}^{15}\text{O}(\alpha,\gamma){}^{19}\text{Ne}$ and ${}^{15}\text{O}(\alpha,p){}^{18}\text{F}$ reactions lead to break out from the CNO cycle to a process of rapid proton capture (rp-process) which involves sequential proton captures out to the proton drip line or until the Coulomb barrier becomes too large. Each of these transitions to higher-temperature reactions lead to orders-of-magnitude increases in the rates of energy production. Thus, in addition to effects on nucleosynthesis, the dynamics of the various high-temperature environments are intimately coupled to the cross sections for proton and alpha-particle capture reactions on unstable nuclei.

Figure 1 Regions of the density vs. temperature plane in which the various hydrogen-burning processes are dominant (from ref. 4). The normal CNO cycle occurs in stars slightly larger than the sun. The hot (beta-limited) CNO cycle is particularly important in supermassive stars. The rp-process is important during the thermonuclear runaways on accreting neutron stars which may be the source of X-ray bursts.

Essentially two different approaches have been attempted to supply the necessary data. The most straightforward approach (which we will call the finesse approach) is to utilize nuclear data obtained by conventional means combined with a model for the nuclear structure and reaction mechanisms to derive the desired input datum. This has been done for the $^{13}\text{N}(p,\gamma)^{14}\text{O}$ reaction^{4,8,9}, and the ^{14}O , ^{15}O , and ^{19}Ne reactions¹⁰ and heavier nuclei¹¹. This approach has been quite productive since many of the reactions of interest are probably dominated by one or a few resonances whose radiative and particle widths can be inferred indirectly. There is still quite a bit that can be done with this approach, for example to better identify the

energies and widths of the resonances of interest. The problem with this approach, however, is that one can never be quite sure that enough physics and input data have been included in the calculations to be confident that the inferred cross section is correct.

The other approach (which we will call the brute-force approach) is to produce a beam of radioactive heavy ions to be focused onto a target of hydrogen or ^4He (or in a few cases to do measurements on a radioactive target¹²). The radioactive ion-beam brute-force approach is much more difficult but may provide more information. Since we have been involved in a modest effort to develop this technology along with a number of other labs¹², we make a few remarks to update the reader as to the current state of the art of our work at LLNL.

The Well-Tempered Radioactive Ion Beam

Trying to do experiments with radioactive ion beams is like trying to play a Bach fugue for the first time. It begins so simply that anyone can do it, but soon becomes very difficult - (sigh). Although the art for measuring reaction rates with radioactive ion beams has been under development for some time^{13,14}, progress has been slow. The main problem is fundamental. The required (p,γ) cross sections involve electromagnetic transitions and are therefore very small (typically ≤ 1 nb at energies of interest away from a resonance). Thus, in addition to the problems of producing, isolating, and focusing a beam of radioactive ions onto a target, one has the problem of extremely low data rates which are easily swamped by the most innocuous of backgrounds. Figure 2 is an example of a ^{13}N beam produced in our quadrupole sextuplet beam transport system (QSBTS)^{12,14} and isolated by time-of-flight discrimination. The beam appears to be well isolated, but even after nine orders of magnitude reduction of the primary ^{12}C beam, the background due to ^{16}O produced by secondary reactions still overwhelms any ^{14}O produced by the $^{13}\text{N}(p,\gamma)^{14}\text{O}$ reaction by three orders of magnitude. Clearly the name of the game is background discrimination without sacrificing data rate.

Our most recent efforts at Livermore have been attempts to reduce the background by the introduction of additional collimation (see Fig. 3), and the procurement of a superconducting beam bunching system for more accurate time-of-flight discrimination of the desired ^{13}N secondary beam. The addition of a Wien filter is also planned.

Another aspect of these measurements which can and should be exploited for the purposes of background reduction is the detection of more than one signal from an event; for example the detection of the gamma-ray as well as the recoil product should help discriminate the background. This is one aspect which has not yet been fully exploited.

Figure 2 ΔE vs. E contours showing the profile of a ^{13}N beam produced by the $^2\text{H}(^{12}\text{C}, n)^{13}\text{N}$ reaction in our QSBTS (Fig. 3). Background events from scattered ^{12}C were eliminated by gating on the time-of-flight (TOF) through the spectrometer.

Along this line I would like to mention an example of a measurement which we are attempting. That is the $^7\text{Be}(p, \gamma)^8\text{B}$ reaction (or more appropriately $^1\text{H}(^7\text{Be}, ^8\text{B})\gamma$). This reaction has the unique aspect that the recoiling ^8B beta decays with a half life of 770 msec into ^8Be which can be detected as two alpha particles. The

Figure 3 The present configuration of our quadrupole sextuplet beam transport system (QSBTS). By demanding a focus at the center, the background is significantly reduced.

detection of these alpha particles when the beam is off can be exploited¹⁵ for the measurement of this cross section. At first sight this seems like a straightforward way to eliminate the background. To our surprise, however, when we removed the secondary target from the beam (see Fig. 3) we found that we could still detect alpha particles. The problem can be explained with reference to Fig. 4 which shows what happened when we put a deuterated polyethylene target in the primary position. The detector lit up with alpha particles. ^8Li produced by the $^7\text{Li}(d,p)^8\text{Li}$ reaction produces nearly the same alpha particle spectrum as that from ^8B . At the level of the natural abundance of ^2H in our primary $(\text{CH}_2)_n$ target, the ^8Li background overwhelms the count rate due to ^8B by three orders of magnitude - (sigh).

Clearly, the problem of the further development of this technology is a formidable one. Nevertheless, the technology has been proven to work for at least some cross sections¹⁴, and considerable further reductions in background can be envisioned with existing technology. One of the most promising possibilities is the acceleration of the beam of interest directly from the ion source. Proposals of this type have been suggested at Berkeley¹² and TRIUMF¹⁶. If sufficiently developed, this approach may best surmount the background problem.

Figure 4 Alpha-particle spectrum from ^8Li decay produced by the $^7\text{Li}(d,n)^8\text{Li}$ reaction.

Figure 5 The mechanisms for neutron-capture nucleosynthesis drawn as lines representing the dominant isotopes produced during the processes (from ref. 17.).

NEUTRON CAPTURE NUCLEOSYNTHESIS

Most nuclides with $A \geq 70$ are synthesized by neutron capture. Figure 5 is from a recent review article¹⁷ on the various stellar processes which lead to neutron capture nucleosynthesis. For the most part, these processes correspond to different time scales. The s-process describes neutron capture on a time scale which is slow compared with typical beta-decay lifetimes near the line of stability, and thus leads to the formation of a continuous chain of stable heavy elements from the iron group to ^{209}Bi . The r-process^{17,18}, on the other hand, corresponds to neutron capture on a time scale which is rapid compared with beta-decay lifetimes. In the limit of high neutron density, this process appears as a chain of isotopes for each element which represent the point of $(n, \gamma) \rightleftharpoons (\gamma, n)$ equilibrium far from stability. The n-process is what actually seems to be predicted by most stellar models¹⁷ for either the r-process or s-process, i.e. a competition between beta decay and neutron capture which can not be treated with the same mathematical simplicity as in the classical s-process and r-process^{17,18}. The p-process is a somewhat less frequent process (as evidenced in abundances) which probably is the result of photodisintegration reactions in high-temperature¹⁹ or high-electron-density²⁰ regimes.

s-Process Studies

Figure 6 is from a recent study²¹⁻²³ of details of s-process nucleosynthesis in the framework of stellar models which produce neutrons by a $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ reaction during sequential thermal pulses in a helium-burning shell²⁴. What is plotted is the σN curve (neutron capture cross section times abundance) for stable isotopes along the chain of elements which are produced in the s-process. This calculation corresponds roughly to the conditions thought to exist in the interior of a 7 $M_{\odot}$ red-giant star on the asymptotic giant branch. In a classical s-process^{17,18} (low neutron density) this would be a smooth curve. However, as variations in the neutron density and temperature are taken into account, the structure observed in this figure emerges. This structure is due to branch points, i.e., unstable nuclei with competing neutron-capture and beta-decay rates.

Figure 6 The σN curve calculated²¹⁻²³ in the framework of stellar models²⁴ for the s-process in thermally-pulsing red-giant stars.

From these kinds of calculations it becomes clear that several kinds of nuclear data are particularly important for the s-process. For one, it is desirable to have neutron capture cross sections for stable nuclei known as well as possible. As we have learned^{21-23,25} already at this conference, it is possible to place rather stringent constraints on the conditions responsible for the s-process when the neutron capture cross sections are well known. At present, a number of neutron capture cross sections are known to an accuracy as good as $\pm 5\%$, largely due to the efforts at Karlsruhe²⁶, and Oak Ridge²⁷ (see ref. 23 for a recent summary of measured cross sections). New technology on the horizon which will make use of 4π BaF₂ scintillators may make it possible to measure relative cross sections to 2% accuracy. This will be extremely useful in clarifying the nature of the s-process environment.

The other data which are required are the beta-decay lifetimes and neutron-capture cross sections for unstable nuclear excited states. Although these quantities are difficult to obtain experimentally, some very useful calculations have been made²⁸ of the effects on the nuclear cross sections from thermally populated excited states, particularly in regards²⁹ to the nuclear cosmochronometer, ¹⁸⁷Os, and the beta decay rates³⁰, although much can still be done to better describe the decay properties of excited states.

Figure 7 is an illustration of some calculated²⁸ thermal correction factors for ground-state cross-sections for a number of isotopes near the line of stability. From this figure it is clear that these correction factors can be as large, $\sim 10\%$, as the uncertainty in the measured cross sections and must be taken into account. One particularly large correction factor is expected for ¹⁹³Pt. Since this nucleus is part of the important branching²¹⁻²³ at ¹⁹²Ir, it would be good to know this correction as well as possible.

TABLE I Some nuclear data which would be most useful for s-process nucleosynthesis.

-
1. Stable nuclei for which the neutron capture cross section has not been measured; ⁶⁶Zn, ⁷²,⁷³Ge, ⁷⁷Se, ⁹⁹Ru.
 2. Important unstable nuclei for which the neutron capture cross section has not been measured; ⁷⁹Se, ⁸⁵Kr, ¹⁰⁷Pd, ¹⁴⁷Pm, ¹⁵¹Sm, ¹⁶⁶Ho, ¹⁸⁶Re, ¹⁹²Ir, ²⁰⁵Pb.
 3. Nuclei with large thermal correction factors for the ground-state neutron capture cross sections; ¹⁰³Rh, ¹¹⁹Sn, ¹⁶⁹Tm, ¹⁸⁷,¹⁸⁹Os, ¹⁹³Pt, ²⁰¹Hg, ²⁰⁵Pb.
 4. Branch points with large corrections for thermally-enhanced beta decay; ⁶⁰Co, ⁶³Ni, ⁷⁹Se, ⁹³Zr, ⁹⁹Tc, ¹⁰⁷Pd, ¹³⁴Cs, ¹⁵¹Sm, ¹⁵²,¹⁵⁴,¹⁵⁵Eu, ¹⁶⁰Tb, ¹⁶³Dy, ¹⁶³Ho, ¹⁷⁶Lu, ¹⁸¹,¹⁸²Hf, ¹⁸⁷Re, ¹⁸⁷Os, ²⁰⁴,²⁰⁵Tl.
-

For the benefit of experimentalists and theorists who might like to attack some of these nuclei, Table I summarizes some of what we consider to be the most important quantities to better refine as input to the s-process.

Figure 7 Correction factors, f , for various isotopes near the line of stability due to the thermal population of excited states at stellar temperatures (from ref. 28). Isotopes with $f > 10\%$ are labeled.

It would of course also be desirable to know neutron capture cross sections away from stability. These cross sections for the most part have been estimated from global Hauser-Feshbach calculations²⁸, although near neutron closed shells direct radiative capture may be more appropriate³¹. Some very useful progress in this regard has been made^{32,33} by the group at Mainz which has utilized data from delayed neutron emission to derive the cross section for the inverse neutron-capture reaction. Investigations like this could be quite useful if enough nuclei can be studied this way.

At least two of the cross sections for unstable nuclei have recently^{34,35} been directly measured at Oak Ridge. These are 2.15×10^5 y ^{99}Tc and 1.5×10^6 y ^{93}Zr . These particular data, together with some nuclear shell model calculations³⁶, have recently³⁷ found an extremely useful role in the interpretation of a long standing astronomical puzzle which we will outline here because it particularly highlights the kind of information which can be gleaned when good nuclear data are available.

Why do you see Technetium in your Telescope?

The observation of spectral lines of the unstable element, Tc (which is probably ^{99}Tc), on the surface of some red-giant stars was, in fact, the first definitive evidence for ongoing neutron-capture nucleosynthesis in stars. But, there is also an apparent problem with the appearance of Tc, since at the temperatures of stellar interiors in this phase of evolution ($kT \sim 30$ keV) the Boltzmann population of excited states in ^{99}Tc , which can undergo Gamow-Teller (GT) allowed decay, may lead to a drastically reduced ^{99}Tc lifetime (~ 1 yr.) in the star (see Fig. 8). Thus, one wonders how it is that Tc ever survives to appear on the surface. The resolution of this problem³⁷ requires two input data. Figure 9 is from recent³⁶ shell-model calculations of the structure of low-lying states in ^{99}Tc and ^{99}Ru . The wave functions from these calculations can be used to estimate the GT matrix element from the decay of the thermally-populated excited states in ^{99}Tc . The second important datum is the ^{99}Tc neutron-capture³⁴ cross section corrected for the capture into thermally-populated excited states. (In this case the correction is probably small²⁸.)

As it turns out, the capture cross section is large and the GT decays are probably slightly hindered relative to previous

Figure 8 A schematic illustration of the low-lying structure of ^{99}Tc and the effect of this structure on the stellar beta-decay half life for ^{99}Tc .

Figure 9 Calculated³⁶ levels in ⁹⁹Tc and ⁹⁹Ru and the isotonic pair, ⁹⁷Nb and ⁹⁷Mo. Calculations like this allow for better determination of the stellar beta-decay lifetimes.

estimates (Fig. 8). Thus, in the stellar environment, the equilibrium abundance of ⁹⁹Tc is very close to the value it would have if it were stable. This is the resolution of the dilemma.

The resolution of this problem leads to an interesting application³⁷ of the cross sections for ⁹⁹Tc and ⁹³Zr (together with stellar observations) as a clock of the lifetime of a thermally-pulsing star in the third dredge-up phase (a period of stellar evolution during which s-process material is recurrently produced and dredged to the surface by deep convection zones). Figure 10 shows how the ratios of Tc to ⁹³Nb (the product from ⁹³Zr decay) or the ratio of Tc to a

Figure 10 Predicted abundance ratios (lines) for (Tc/Nb) and (Tc/Mo) as a function of the lifetime of a red-giant star in the thermally-pulsing third dredge-up phase (from ref. 37). The points are observations. The fact that the two abundance ratios give the same lifetime shows how these data can be used to measure the lifetime of a star in this phase.

stable element like Tc/Mo vary with time and can be used as a clock for the star. The two stars (R Cmi and CY Cyg) for which these ratios have been measured agree very nicely with the prediction. Thus, here is a case in which refined nuclear input data have led to a clearer picture of stellar structure and evolution.

The r-Process

Before leaving the subject of neutron-capture nucleosynthesis, we should say a word or two about the r-process. The required nuclear input data are summarized in detail elsewhere^{17,42}. We repeat the list of some of the most immediate needs in Table II. The astrophysical site for the r-process is still not known, although a number of promising possibilities have been proposed^{17,18,38-40}. Basically there are two fundamental time scales which must be determined from better nuclear input data before the ambiguity surrounding the r-process site can be resolved. One is just how high the neutron density must be to reproduce the r-process abundances. This quantity depends on the

ratios of neutron-capture to beta-decay rates. For some scenarios⁴¹ it is possible to reproduce the observed r-process abundances without reaching (n, γ) equilibrium. Then the abundance peaks will largely be determined by the neutron capture cross sections away from stability as illustrated in Figure 11 (taken from ref. 40). If (n, γ) equilibrium is achieved, then the abundances will be determined by the beta-decay rates of unmeasured nuclei far from stability. Although some progress has been made³⁹ in shell model calculations of these rates, further studies are warranted before the issue is settled.

The second quantity which must be determined for the r-process is the dynamical time scale during which the neutron density must remain high in order to produce the actinides (which can not be produced by the s-process due to alpha particle decay at ²¹⁰Bi). This quantity depends on the sum of the neutron-capture and beta-decay lifetimes as one moves away from stability. Essentially, the r-process must live long enough for nuclei to capture out to far from stability and then beta decay up to the mass numbers of the actinides. This places a severe constraint on dynamical processes such as shock-driven explosive helium burning during a supernova^{38,39}. At present, it appears that the calculated beta-decay rates are too slow by about a factor of five for this mechanism to be viable. Clearly, more refined determinations of neutron-capture cross sections and beta-decay rates are desired before the astrophysical site for the r-process can be determined.

Figure 11 n-Process steady-flow calculations of Cameron et al.⁴¹. The upper curve shows the observed r-process abundances. The second curve is the calculation. The third and fourth curves show the contributions of beta-decay and beta-delayed neutron emission to the calculated structure.

Table II Some nuclear data needs^{17,42} for the r-process. The numbers represent an approximate priority for the measurements. Asterisks indicate quantities which have been measured. The quantities are: the neutron binding energies, B_n , the beta-decay half life, τ_β , beta-delayed neutron emission, $n(\beta)$, energies and spins of low-lying states, E_i , j_i .

Nucleus			Priority of Measurements					Comment
A	Z	N	B_n	τ_β	$n(\beta)$	E_i	j_i	
78	28	50	1	2	3	4	5	r-process path
79	29	50	1	2	3	4	5	r-process path
79	30	49	1	2	3	4	5	decay back
79	31	48	*	*	-	1	2	decay back
80	29	51	2	3	1	4	5	$\sigma(n,\gamma)$ from n_β
80	30	50	1	2	3	4	5	r-process peak
80	31	49	1	*	*	2	3	decay back
81	31	50	1	*	*	2	3	r-process path
128	46	82	1	2	3	4	5	r-process path
129	48	81	1	2	3	4	5	decay back
129	47	82	1	2	3	4	5	r-process path
130	47	83	2	3	1	4	5	$\sigma(n,\gamma)$ from n_β
130	48	82	1	2	3	4	5	r-process peak
130	49	81	1	*	*	2	3	decay back
130	50	80	*	*	-	*	1	decay back
131	48	83	1	2	3	4	5	r-process path
131	49	82	1	*	*	2	3	r-process path
131	50	81	*	*	-	*	1	r-process path
192	66	126	1	2	3	4	5	r-process path
193	67	126	1	2	3	4	5	r-process path
194	68	126	1	2	3	4	5	r-process path
195	68	127	2	3	1	4	5	$\sigma(n,\gamma)$ from n_β
195	71	124	3	2	1	4	5	decay back
195	70	125	2	3	3	4	5	decay back
195	69	126	1	2	3	4	5	r-process peak
196	70	126	1	2	3	4	5	r-process path
197	71	126	2	3	1	4	5	r-process path
Z=40 - 50			1	2	3	4	5	r-process path
($B_n \sim 0 - 4$ MeV)								
Z=60 - 70			1	2	3	4	5	r-process path
($B_n = 0 - 4$ MeV)								
Z=50 - 60, 70 - 90			1	2	3	4	5	r-process path
($B_n = 0 - 4$ MeV)								
Z=40 - 90			1	2	3	4	5	approach to r-process path & test of model extrapolations

CONCLUSION

The field of nuclear astrophysics still contains many unanswered and baffling questions. In this brief overview it is hoped that the reader has received a picture of how more and better nuclear data can help to push back the frontiers in nuclear astrophysics.

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