Rp-process-motived experimental initiatives at NSCL

F. Montes

Joint Institute for Nuclear Astrophysics, http://www.jinaweb.org, USA, and National Superconducting Cyclotron Laboratory, Michigan State University, E. Lansing, MI 48824, USA

INTRODUCTION

Type I X-ray bursts are the most frequent type of thermonuclear explosion in the Galaxy. In such events, the neutron star in a binary system experiences a dramatic increase in brightness on a timescale of a few seconds. The explosion is powered by a thermonuclear runaway when the heating resulting from the accumulation of matter on the surface of the neutron star cannot be compensated by readjusting the stellar structure or by surface cooling[1]. This increase in temperature leads to higher nuclear reaction rates which result in a more rapid temperature increase. The resulting burst has a typically energy output of 10^{39-40} ergs (more than 1000 times more than the sun during the same period of time) and lasts typically 10-100 seconds. During the flash, it is expected that 90% of the previously accreted hydrogen and helium is transformed into carbon and heavier elements[2]. Observations of such events provide information about the properties of matter under extreme conditions by providing constraints in the system parameters such as neutron star properties, thermal state of the neutron star crust, accretion rate, ignition mechanism, etc.

X- ray bursts have been observed in approximately 90 sources that show a recurrence times of hours up to days[3]. Although X-ray burst have been observed since the 1970's, a dramatic increase over the last decade in observational data has led to new discoveries and large catalogues [4, 5] that allow for the first time a meaningful comparison between bursts (due to uniform and updated analysis procedures) and the study of bursters outside the typical burst behavior. Although much progress has been obtained in our understanding of these processes, several open questions remain. As an example the recent observation of short recurrence times (less than 10 minutes) do not agree with current X-ray burst models. The short recurrence time is too short for the accretion rate to accumulate enough fuel to burn in the burst. Although, this seems to indicate that unburned fuel from previous X-ray bursts is being used, the mechanism for halting burning once an X-ray burst starts is still unknown. Both stellar (fast rotation mixing, burning occurring in a hydrogen-depleted layer, etc.) and nuclear physics causes (nuclear waiting points)[3] may be responsible for halting and then re-igniting the short recurrence time X-ray bursts. In order to fully understand these and other observations (millisecond burst oscillations, burst dependence on accretion rate, superburst fuel origin, crust processes, multi-peaked bursts, change in burst behavior as a function of time), current nuclear physics uncertainties need to be reduced.

RP-PROCESS

Once the burst is triggered by the 3α reaction, the temperature of the exploding layer quickly increases triggering first a sequence of mainly (α,p)-(p,γ) reactions (the so-called αp-process) followed by hydrogen burning via the rapid proton capture process (rp-process). The rp-process is the main source of energy and determines the X-ray light curve. Quantitative comparison between X-ray burst calculations and typical X-ray bursts have shown excellent agreement[6] but have also shown that the nuclear physics of the rp-process are not sufficiently accurate to test X-ray bursts at the level provided by observations[13]. The αp-process path on the chart of nuclides follows a competition between (α,p) reactions (allowed by the increasing temperatures in the early phase of an X-ray burst) and proton captures up to mass $\approx$40. An effective way to avoid long β-decays (compared to the other rates) is by having an (α,p) reaction followed by a proton capture. The main sequence starts with ^{14}O(α,p)^{17}F(p,γ)^{18}Ne and continues until ^{38}Ca(α,p)^{41}Sc is reached. For heavier nuclei up to mass $\approx$64-100, the rp-process path is dominated by proton captures and β-decays.

NUCLEAR PHYSICS

In order to determine important uncertainties in current X-ray burst models, studies examining nuclear reaction sensitivities have been performed in the past[7, 8]. In those studies, key nuclear reactions whose uncertainties have the largest impact were identified. Since the direct measurements of most nuclear reactions are not feasible with current facilities (except in a few cases such as ^{13}N(p,γ)^{14}O[9, 10] at Louvain-la-Neuve and ^{21}Na(p,γ)^{22}Mg[11] at TRIUMF), indirect methods are usually employed. A few experiments have been performed to study (α,p) and (p,α) directly[12]. When the reaction has to be studied indirectly, knowledge of excitation energies, Q-values, spin assignments, single-particle strengths and spectroscopic information are required. Nuclear masses are needed for the determination of resonance energies, which enter exponentially in the reaction rates and have to be known to better than 10 keV when a few resonances dominate the reaction rate[1]. Such precision has been obtained for the Q-values of lighter nuclei (Z<23) in the rp-process path but only in some cases for heavier nuclei. In cases where the (p,γ) Q-value is small or negative, an equilibrium between proton capture and its inverse photo-disintegration is established. In those cases, the Q-value has to be known with a precision of better than 100 keV. Waiting points with a relatively long β-decay half-lives and a proton unstable neighboring $Z+1$ nucleus such as ^{68}Se and ^{72}Kr, are examples. These nuclei (along with ^{64}Ge) in particular are responsible for the rate of energy release and the long tails observed in some bursts[13]. Although the mass of the waiting point isotopes have been measured, the Q-values have been obtained from theoretical estimates since the p-capture nuclei are particle-unstable. A recent experiment at the National Superconducting Laboratory (NSCL) has been performed to address the nuclear physics uncertainty in the lifetime of ^{68}Se by measuring the β-delayed proton emission of ^{69}Kr. By measuring the proton emission from low lying β-decayed states in ^{69}Br, the proton separation of ^{69}Br can be constrained. Analysis of the experiment is currently underway.

Although considerable progress has been made, most of the reactions studied experimentally so far are limited to nuclei in the rp-process path close to stability. Most of the reactions used in X-ray burst models are theoretical estimates based on statistical Hauser-Feshbach calculations[14]. Shell model calculations[15, 16] are limited to available configuration spaces. Energies of individual states can be estimated with shell model calculations with a precision at best of around 100 keV which translates into many orders of magnitude uncertainties. For a review of recent measurements using both direct and indirect techniques see [1].

REA3 REACCELERATED BEAM FACILITY

The ReA3 reaccelerated beam facility currently under construction at NSCL will provide low energy rare isotope beams ideally suited for astrophysics studies. The beams produced by fragmentation will stop in a gas-stopper before being reaccelerated in a superconducting LINAC to energies from 0.3 to 6 MeV/u. ReA3 will provide rare isotope beams of many elements that are currently unavailable or chemically difficult to produce in other rare beam facilities. The possibility to measure nuclear reaction rates at the astrophysically relevant energies for nuclei directly in the rp-process path will provide exciting science opportunities. Figure 1 shows expected ReA3 intensities.

Scientific equipment currently under development that will be used for rp-process motived experiments include ANASEN and the Active Target Time Projection Chamber (AT-TPC). The AT-TPC is being built by a collaboration of researchers from MSU, University of Notre Dame, Western Michigan University, LLNL, LBNL, and St. Mary's University. The time projection chamber detector will be placed inside a large solenoid so once the beam particles enter the gas chamber, they can interact with the active target. The resulting products will be tracked within the gas vessel of the time projection chamber. It is planned to be used for the indirect study of reactions of astrophysical interest either by (d,p) or (^{3}He,d) transfer reactions. The Array for Nuclear Astrophysics Studies with Exotic Nuclei (ANASEN) is a charged-particle detector array being developed by Louisiana State University and Florida State University and it consists of silicon-strip detectors backed with CsI scintillators arranged in a barrel configuration, and an annular Si detector enclosing the downstream end of the barrel. A gas proportional counter is also planned. It will initially be used for proton scattering, (α,p), (p,α) and (d,p) reaction studies.

The Separator for Capture Reactions (SECAR) is a highly specialized device also planned to be used in ReA3. This recoil separator will be used for the direct measurement of (p,γ) reactions at astrophysically relevant energies. Although the focus will be on X-ray bursts and novae, it will also address reactions relevant for late burning stages and explosive nucleosynthesis in supernovae. Although with ReA3, SECAR will be fully operational and first direct measurements will be carried out, only the Facility for Rare Isotope Beams (FRIB) will provide the beam intensities needed for direct measurements of a wide range of reaction rates.

We thank H. Schatz for useful discussions concerning this manuscript. This work was supported by NSF grants PHY 08-22648 (Joint Institute for Nuclear Astrophysics) and PHY 01-10253.

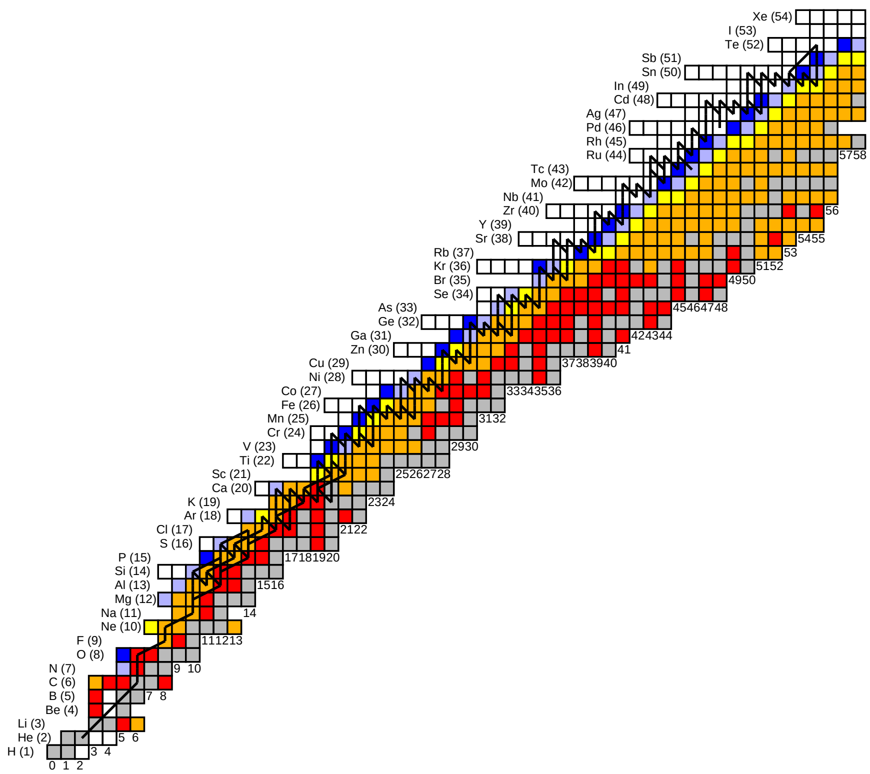

FIGURE 1. Expected ReA3 intensities and the main path of the r-process in a 1-zone rp-process model[17]. Stable nuclides are shown in gray, nuclides with intensities greater than 10^5 particles per second (pps) are shown in red, 10^4 pps in orange, 10^3 pps in yellow, 10^2 pps in light blue and 10 pps in dark blue.

REFERENCES

1. Schatz, H., & Rehm, K.E. 2006, Nucl. Phys. A, 777, 601
2. Woosley, S.E. et al. 2004, ApJS, 151, 75
3. Keek, L., Galloway, D.K., in't Zand, J.J., & Heger, A. 2010, ApJ, 718, 292
4. Galloway, D.K., et al.. 2008, ApJS, 179, 360
5. Multi-INstrument Burst ARchive - MINBAR, http://users.monash.edu.au/ dgallow/minbar/
6. Heger, A., Cumming, A., Galloway, D.K., & Woosley, S.E. 2007, ApJ, 671, 141
7. Parikh, A., Jose, J., Moreno, F., & Illiadis, C. 2008, ApJS, 178, 110
8. Amthor, M.A., et al. 2006, PoS (NIC-IX), 068
9. Decrock, P. et al. 1991, Phys. Rev. Lett., 67, 808
10. Delbar, P. et al. 1993, Phys. Rev. C, 48, 3088
11. Bishop, S. et al. 2003, Phys. Rev. Lett., 90, 162501
12. Deibel, C.M., et al. 2011, PoS (NIC-XI), 056
13. Brown, B.A. et al. 2002, Phys. Rev. C, 65, 045802

14. Rauscher, T., & Thielemann, F.K. 2000, At. Data Nucl. Data Tables, 75, 1
15. Herndl, H. et al. 1995, Phys. Rev. C, 52, 1078
16. Fisker, J.L., et al. 2001, At. Data Nucl. Data Tables, 79, 241
17. Schatz, H. et al. 2001, Phys. Rev. Lett., 86, 3471