

Nuclear astrophysics (see slides in Section 2.1c)

References:

- 1) Hans A. Bethe and Gerald Brown, “How a Supernova Explodes”, Scientific American (May 1985)
- 2) RIA Physics White Paper (Nucl. physics conference at Raleigh, NC, summer 2000)

Nuclear Astrophysics is a broad interdisciplinary field that ties microscopic nuclear and particle physics with macroscopic stellar and cosmological events. It involves the physics of nuclear matter, the understanding of nuclear reaction mechanisms, the evolution of nuclear structure, and the contributions of strong and weak interaction processes resulting in stellar nucleosynthesis and energy generation. The strong interaction and nuclear reaction processes determine the time scales of stellar evolution and the origin of the chemical elements in our universe, while weak interaction processes are closely associated with the physics of core collapse type II supernovae. Nuclear reactions on unstable short-lived species determine the time scale, the energy release, and the ensuing nucleosynthesis in violent stellar explosions. The supernovae shock front driven through the outer layers of a presupernovae star, thermonuclear explosions on the surface of accreting white dwarf stars or neutron stars, and rapid burning in the accretion disks of black holes are only some of the sites where nucleosynthesis proceeds far away from the line of stability.

The rapid neutron capture process (r-process)

The r-process occurs in “Type II supernovae” explosions, following the collapse of the inner core of the star. Hence, these supernovae are often referred to as “core collapse supernovae”. According to astrophysics theories, Type II supernovae occur in massive stars whose mass exceeds about 8 solar masses.

As first explained by Hans Bethe at Cornell University in 1939, stars create energy by nuclear fusion. A massive star will initially produce energy via “hydrogen burning” to form helium ($Z = 2$) nuclei, which takes about 7 million years for a star with mass $M = 25$ solar masses. When the hydrogen in the core of the star is exhausted, the core contracts due to gravitational pressure which heats it enough to ignite the fusion of helium into carbon. This helium burning phase lasts about 500,000 years. This is followed by the carbon ($Z = 6$) burning phase (600 years), neon ($Z = 10$) burning phase (1 year), oxygen ($Z = 8$) burning phase (6 months), and finally the silicon ($Z = 14$) burning phase (1 day). The (incomplete) nuclear fusion of 2 silicon nuclei produces an iron nucleus ($Z = 26$).

As a result of the above-mentioned fusion cycles, the star assumes an onion-like structure: the most massive nuclei (iron) are in the interior and the lightest nuclei (hydrogen) are in the outermost region: the core of the star is made of iron, followed by a shell of silicon plus sulphur, then a shell of oxygen plus neon, followed by a carbon + oxygen shell, then a helium region, and finally a large region of hydrogen in the outermost layer.

Since the maximum nuclear binding energies occur in the mass 60 region (iron, nickel), energy gain via nuclear fusion is no longer possible. The mass of the core reaches and exceeds the “Chandrasekhar limit” which for a very heavy star is about 1.2 – 1.5 solar masses. This mass limit results from the balance of attractive gravitational interaction and repulsive electron gas pressure (relativistic Fermi gas). For details, see Heyde’s textbook, chapter on Fermi gas.

Finally, the core of the massive star collapses under its own gravitational pressure in less than a second! The core reaches a density comparable to that of nuclear matter, i.e. $\rho_0 = 0.17 fm^{-3}$. Under these conditions, the electrons are very close to the nucleus resulting in enhanced “electron

capture” via

$$p + e^- \rightarrow n + \nu_e .$$

This process is of the utmost importance: it explains that a large fraction of protons will be turned into neutrons leading to the formation of a “neutron star”, and in addition lots of high-energy neutrinos will be produced. The “neutrino wind” drives the supernova explosion of the star. Apart from Hubble Space Telescope pictures of the supernova explosion in the visible part of the light spectrum (see slides 4 and 5 in Section 2.1c), it is possible to “see” the neutrino flux with the Kamiokande neutrino detector in Japan. The high-energy neutrino burst provides an additional, independent confirmation of the supernova explosion. This theoretical scenario was spectacularly confirmed during the Supernova 1987a event.

We are now in a position to understand the rapid neutron capture process (r-process) following a core-collapse supernova explosion. The r-process together with the slow neutron capture process (the s-process) is a dominant nucleosynthetic mechanism for heavy elements above iron. The r-process path through the nuclear chart is shown in slides 1-3 of section 2.1c. In the r-process, starting from a seed nucleus (e.g. ^{56}Fe), the rapid capture of neutrons leads to heavier and heavier isotopes until a nucleus is reached whose neutron binding energy is so small that the neutron capture rate is balanced by photo-disintegration. At this point, the neutron capture process stops and the nucleus has to wait for a β -decay leading to an element with higher neutron separation energy where the capture process can start again. Nuclei with neutron magic numbers, therefore, tend to be “waiting points”, where the neutron capture hesitates and β -decay towards stability predominates. This results in the maxima observed in the cosmic element abundances at certain mass numbers (see slide 6 in Section 2.1c). The deduced r-process abundance distribution is, therefore, one of Nature’s signatures for the existence of shell structure in very neutron-rich nuclei. In particular, the theoretically predicted “quenching” of the shell structure near the neutron dripline (see slide 7 in section 2.1c) can have a dramatic effect on calculated abundances.

The origin of the r-process is still under debate: Neutrino driven winds in supernovae or merging neutron stars are two of the proposed environments. Present models of the r-process are based on global calculations for characteristics of very neutron rich nuclei. Recent experiments with first generation exotic beam facilities have revealed significant discrepancies with predicted nuclear properties such as masses, decays, resonance energies, and shell structure.

To understand nucleosynthesis, and the stellar processes and sites that produce it, it is necessary to perform experiments on nuclei far from stability. RIB facilities will enable us, for the first time, to put our understanding of most of explosive nucleosynthesis and the nature of stellar explosions on a firm experimental basis.

The rapid proton capture process (rp-process)

Novae and x-ray bursts are the most common explosive astrophysical events and, thus, have been studied extensively with both ground and space-based telescopes. These events occur, as do Type Ia supernovae, in binary systems where one of the objects is a white dwarf or a neutron star. Due to their strong gravitational potential, these compact objects accumulate hydrogen and helium from their companion star onto their surfaces where it is ignited, once sufficient material has piled up. At low accretion rates on a white dwarf this triggers a nova explosion, while high accretion rates trigger a Type Ia supernova. Low accretion rates on a neutron star result in x-ray bursts lasting typically tens of seconds. All these events involve nuclear reactions at high temperatures ($> 10^8$ K) and high densities and are responsible for the synthesis of a considerable fraction of the elements with masses above oxygen.

Novae are potential producers of ^{18}F , ^{22}Na , and ^{26}Al , which are sources of observed galactic gamma rays. Modeling of their nucleosynthesis requires reaction rates for proton and α capture processes on light neutron deficient nuclei. The experiments are extremely difficult and require beam intensities of up to 10^{12} particles per second. Reliable experimentally measured reaction rates will allow the detailed simulation of nucleosynthesis to be compared with the observational results and offer the opportunity to probe directly the macroscopic conditions in extreme thermonuclear explosions.

The phenomena of x-ray bursts and x-ray pulsars are interpreted as thermonuclear explosions in the accreted hydrogen and/or helium rich layers of neutron stars. These events offer the opportunity to study nucleosynthesis at extreme temperature and density conditions on a time scale of only a few seconds and to obtain information on neutron star properties. The ignition of this thermonuclear runaway depends on the break-out reactions from the hot CNO cycles; the time scale for the energy release depends on alpha and proton capture reactions and beta decay processes near the reaction path. The peak of the energy generation is associated with the doubly closed shell nucleus ^{56}Ni . The endpoint of the rp-process depends on subtleties of nuclear structure near the $N=Z$ line, and is most likely linked to the onset of alpha decay from the neutron deficient Te isotopes back to the $Z=50$ (closed shell) Sn isotopes.

To study the onset of the rp-process, reaction rate information is necessary, and much of this information can only be garnered with the use of unstable ion beams. The anticipated cross sections are extremely small and require high beam intensities. Of extreme importance is the measurement of waiting points along the rp-process path. The predicted 2p-capture process (bridging the limits of particle stability by involving proton capture on proton unstable nuclei) and the prediction of four $^1\text{H} \rightarrow ^4\text{He}$ hydrogen-burning cycles (involving Sn-Sb-Te nuclei) both need to be experimentally verified to determine the fate of hydrogen in the accreted material and the abundance distribution in the ashes, which are being buried by freshly accreted material on the surface of the neutron star. Remaining hydrogen is converted by electron capture to neutrons possibly igniting an r-process in the deeper layers of the neutron star atmosphere. Still deeper, in the neutron star crust, the ashes will be converted by electron capture from neutron deficient to neutron rich material and will subsequently neutronize by a combination of electron captures and pyconuclear processes along the neutron drip line. These reaction sequences determine observable neutron star properties like the thermal structure of the neutron star crust and the emission of gravitational waves.