Nuclear astrophysics of the s and r-process

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In 1938, the quest for the energy production in stars had been solved by the work of Bethe and Critchfield [1], von Weizsäcker [2], and Bethe [3], but the origin of the heavy elements remained a puzzle for almost two more decades. It was finally the discovery of the unstable element technetium in the atmosphere of red giant stars by Merrill in 1952 [4], which settled this issue in favor of stellar nucleosynthesis, thus questioning a primordial production in the Big Bang. A stellar origin of the heavy elements was strongly supported by the increasingly reliable compilations of the abundances in the solar system by Suess and Urey [5] and Cameron [6], because the pronounced features in the abundance distribution could be interpreted in terms of a series of nucleosynthesis scenarios associated with stellar evolution models. This key achievement is summarized in the famous fundamental papers published in 1957 by Burbidge, Burbidge, Fowler and Hoyle (B^2FH) [7] and by Cameron [8, 9].

While the elements from carbon to iron were found to be produced by charged particle reactions during the evolutionary phases from stellar He to Si burning, all elements heavier than iron are essentially built up by neutron reactions in the slow (s) and rapid (r) neutron capture processes as they were termed by B^2FH.

The s process, which takes place during He and C burning, is characterized by comparably low neutron densities, typically a few times 10^8 cm^{-3}, so that neutron capture times are much slower than most β decay times. This implies that the reaction path of the s process follows the stability valley with the important consequence that the neutron capture cross sections averaged over the stellar spectrum are of pivotal importance for the resulting s abundances. Although the available cross sections under stellar conditions were very scarce and rather uncertain, already B^2FH could infer that the product of cross section times the resulting s abundance represents a smooth function of mass number A. In the following decade, the information on cross section data was significantly improved by dedicated measurements [10], leading to a first compilation of stellar (n, γ) cross sections by Allen, Gibbons and Macklin in 1971 [11]. Meanwhile, Clayton et al. [12] had worked out a phenomenological model of the s process, assuming a seed abundance of ^{56}Fe exposed to an exponential distribution of neutron exposures with the cross section values of the involved isotopes in the reaction path as the essential input.

As the cross section database was improved, this classical model turned out to be extremely useful for describing the s-process component in the solar abundance distribution. In fact, it turned out that the s process itself was composed of different parts, i.e. the weak, main, and strong components as shown by Seeger et al. [13]. This s-process picture was eventually completed by the effect of important branchings in the reaction path due to the competition between neutron capture and β^--decay of sufficiently long-lived isotopes [14]. The appealing property of the classical approach was that a fairly comprehensive picture of s process could be drawn with very few free parameters and that these parameters are directly related to the physical conditions typical for the s process environment, i.e. neutron fluence, seed abundance, neutron density, and temperature. Moreover, it was found that reaction flow equilibrium has been achieved in mass regions of the main component between magic neutron numbers, where the characteristic product of cross section and s abundance, $\sigma N(A)$ is nearly constant. In spite of its schematic nature, the classical s process could be used to reproduce the solar s abundances within a few percent.

Nevertheless, the more accurate cross section data became available, particularly around the bottle-neck isotopes with magic neutron numbers and in s-process branchings, the more inherent inconsistencies of the classical model came to light [15, 16], indicating the need for a more physical prescription based on stellar evolution [17]. This transition started with early models for stellar He burning by Weigert [18] and Schwarzschild and Härm [19], which were used by Sanders [20] to verify implicit s-process nucleosynthesis. The connection to the exponential distribution of neutron exposures postulated by the classical approach was ultimately provided by Ulrich [21] who showed that this feature follows naturally from the partial overlap of s-process zones in subsequent thermal instabilities during the He shell burning phase in low-mass asymptotic giant branch (AGB) stars. Consequently, the classical approach had been abandoned as a serious s-process model, but continued to serve as a convenient approximation in the mass regions between magic neutron numbers with constant $\sigma \mathrm{N}_s$ products.

The second half of the solar abundances above iron is contributed by the r process. In this case, the neutron densities are extremely high, resulting in neutron capture times much shorter than average β decay times. This implies that the reaction path is shifted into the neutron-rich region of the nuclide chart until the (n, γ) sequence is halted by inverse (γ, n) reactions by the hot photon bath. Contrary to the s process, where the abundances are dependent on the cross section values, the r abundances are determined by the β-decay half lives of these waiting points close to the neutron drip line.

As the consequence of the explosive supernova scenario suggested by B^{2}FH, prescriptions of the r-process abundances were severely challenged by the fact that the required nuclear physics properties for the short-lived, neutron-rich nuclei forming the comprehensive reaction network far from stability were essentially unknown. This information includes β-decay rates and nuclear masses, neutron-induced and spontaneous fission rates, cross section data, and β-delayed neutron emission for several thousand nuclei. First attempts to reproduce the r-process abundances that had been inferred by subtraction of the s abundances from the solar values [11] started with a simplified static approximation, assuming constant neutron density and temperature ($n_n \geq 10^{20}$ cm^{-3}, $T \geq 10^9$ K) during the explosion and neglecting neutron-induced reactions during freeze-out [13]. Early dynamic r-process models were facing not only enormous computational problems, but had to deal with the many unknowns of the possible scenarios. In general, supernovae were preferred over supermassive objects and novae as potential r-process sites [22], but the relevant features of such explosions, i.e. the temperature and density profiles, the velocity distribution during and shortly after the explosion, and the initial seed composition, were too uncertain to draw a plausible picture of the r process by the end of the 1970ies [23].

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