The (Hot) R-Process Scenario: From Reaction Equilibria to Kilonovae

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INTRODUCTION

The recent discovery of a binary neutron star merger (NSM) and a subsequent optical light curve that matches the theoretical predictions for a kilonova (also called macronova) [1] is the first-ever direct evidence of r-process nucleosynthesis in our universe. Hydrodynamical simulations of these events show that the ejecta can be categorized according to their ejection method into three components: (a) dynamical ejecta, (b) neutrino-driven wind ejecta, and (c) unbound material from the accretion disk that forms around the central object (e.g., [2, 3]).

In this article, the r-process is reviewed on the example of a very neutron-rich, fast expanding trajectory representing the dynamical ejecta from the merger of two neutron stars with 1.4 $M_\odot$ each from Ref. [4].

THE MAIN R-PROCESS IN DYNAMICAL EJECTA

For our examplary trajectory, we can distinguish five different phases.

Phase 1: Nuclear Statistical Equilibrium. The initial phase is characterized by high temperatures and densities, which means that nuclear statistical equilibrium (NSE) prevails and the abundances of the individual nuclear species can be derived by means of the NSE equations. This has the advantage that no initial composition is required, as long as the electron fraction Y_e is known.

Phase 2: Cold R-Process. Due to the fast expansion, the temperature and density drop quickly. Neutron captures and β-decays start to produce heavy nuclei, although the β-decay waiting points around the closed neutron shells at $N = 50, 82, 126$ need to be overcome first.

Phase 3: Hot R-Process. Due to nuclear heating, the temperature increases once the full r-process reaction flow is established, despite the ongoing expansion of the ejecta. Under these conditions, photodisintegrations can effectively counter neutron captures close to the neutron drip line and local (n,γ)-(γ,n) equilibria arise. The most abundant isotope (Z, A) in each isotopic chain can be estimated using the following formula (see, e.g., Ref. [5]):

$$S_n(Z, A+1) = -k_B T \ln \left[\frac{G(Z, A+1)}{2G(Z, A)} \left(\frac{A+1}{A} \right)^{3/2} \left(\frac{2\pi\hbar^2}{m_u k_B T} \right)^{3/2} n_n \right] \tag{1}$$

Eq. 1 can be used as a simple tool to estimate where the r-process reaction flow is passing through for a given hydrodynamical trajectory, as long as the neutron density and temperature are high enough for the operation of a hot r-process. For instance, according to the formula, the r-process path is passing through ^{137}In for a wide range of r-process conditions. Figure 1 shows the impact of varied reaction rates of ^{136}In(n, γ), ^{137}In(n, γ) (and their reverse rates), as well as the β-decay of ^{137}In, on the example of NSM dynamical ejecta. The upper and lower values for the β-decay variation are chosen according to the reported uncertainty in the recent measurements of Ref. [6]. For a trajectory of a magneto-hydrodynamically driven supernova [7], the relative abundance changes are even up to 50% for the final abundances of ^{137,138}Ba.

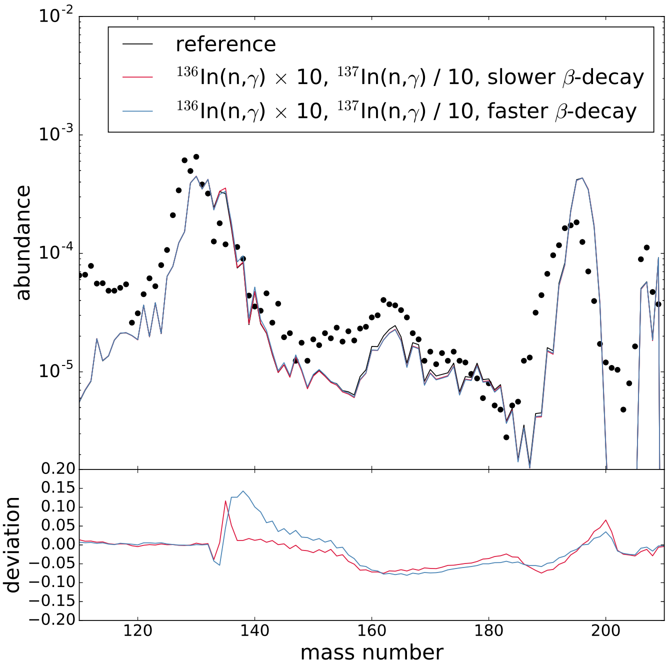

FIGURE 1: Sensitivities of the final abundances of dynamical NSM ejecta to the reaction rates producing and destroying ^{137}In. The neutron captures and their reverse (γ,n) reactions have been modified by a factor of ten, while the β-decay rate of ^{137}In has been modified according to the lower and upper uncertainty limit set by recent measurements [6].

Phase 4: Freeze-out. The nuclear composition starts to decay towards stability when the neutron supply is depleted. The heaviest nuclei on the original r-process path decay by fission or α-decays. The fission products are fragments, mainly in the mass region $120 < A < 150$, and neutrons, which can be captured by nuclei, thus altering the abundance pattern throughout all mass numbers. See Refs. [8, 9] for more details.

Phase 5: Kilo-/Macronova. The aftermath of an r-process environment is characterized by β- and α-decays as well as fission. The radioactive decays power an electromagnetic light curve which can be observed as a so-called kilonova (or macronova). The composition of the ejecta determines the evolution of the light curve and the wavelength at which maximum intensity is achieved. Low-Y_e material produces a large amount of lanthanides, which are known to have very high opacity. Therefore, the light curve originating from such a composition reaches maximum intensity only after about one day and peaks in the red wavelength, while ejecta with a higher Y_e have considerably lower opacities and peak earlier and at smaller wavelengths. In the case of the observed kilonova of GW170817, both components were observed, hinting at the presence of both low-Y_e and high-Y_e ejecta in the same event.

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