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Physical conditions for the r-process

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Abstract. Recent works show that the r-process can proceed by competition between neutron capture and β-decay in low temperature environments (< 5 × 10⁸ K; cold r-process) where photodisintegration plays no role. This is in contrast to the traditional picture of the r-process in high temperature environments (∼ 1 × 10⁹ K; hot r-process) where the (n,γ)–(γ,n) equilibrium holds. In this study, we explore nucleosynthesis calculations based on a site-independent model to elucidate the physical conditions leading to cold and hot r-processes.

Keywords: nuclear reactions, nucleosynthesis, abundances

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INTRODUCTION

Astrophysical origins of the r-process nuclei are still unknown. The most favored scenario in the past decades, the proto-neutron star (NS) wind of core-collapse supernovae (SNe), is facing a severe problem; the neutrino-driven ejecta are proton-rich (or only slightly neutron-rich) [1, 2, 3]. Another favored scenario, the binary merger of NS–NS (or NS–black hole) systems, shows some promise [4, 5, 6, 7], which is however under debate from a point of view of Galactic chemical evolution [8, 9, 10]. Other alternatives that should be explored further are also proposed [11, 12, 13].

In addition to the astrophysical r-process site, we are facing another problem that is essential to the mechanism of the r-process itself. Wanajo [14] has argued that the r-process can proceed by competition between neutron capture and β-decay when matter quickly expands and temperature drops so rapid (below < 5 × 10⁸ K; cold r-process, see also [15, 16]) that photodisintegration becomes unimportant. This is in contrast to the traditional picture of the r-process in high temperature environments (∼ 1 × 10⁹ K; hot r-process) where the (n,γ)–(γ,n) approximately holds [17, 18].

In this study, we explore nucleosynthesis calculations based on a site-independent model to elucidate the physical conditions that lead to cold and hot r-processes. We also discuss crucial differences in the abundance distributions between cold and hot r-processes, which should be tested in future studies of spectroscopic analyses of Galactic halo stars as well as of nuclear experiments.
SITE-INDEPENDENT MODEL

Site-independent approaches are quite useful to study the underlying physics of the r-process, being independent of (in many cases) highly uncertain astrophysical models. Previous site-independent studies were generally based on combinations of constant temperature \(T\), neutron number density \(N_n\), and time duration of neutron irradiation (or number of captured neutrons) \[18, 20\]. However, such approaches cannot account for time-evolutions of \(T\) and \(N_n\), making it difficult to associate with (still unknown) realistic astrophysical conditions. Other parametric studies taking time-evolutions of \(T\) and density \(\rho\) into account were mostly aimed to mimic the physical conditions relevant to the proto-NS winds of SNe (e.g., \[19\]).

Instead, we consider a site-independent model with sets of entropy per nucleon \(S\); in units of the Boltzmann constant, hereafter), expansion timescale \(\tau\); in units of ms, hereafter), and electron fraction \(Y_e\); proton-to-baryon ratio) as free parameters, in which time-evolutions of \(T\) and \(\rho\) are also considered. The temperature as a function of time \(t\) (Figure 1) is assumed to be

\[
T(t) = T_i \exp(-t/\tau) + a f(t) t^{-2/3},
\]

where \(T_i = 1 \times 10^{10}\) K is the initial temperature taken to be a constant value. As shown in Figure 1 (red line), the first and second terms in Equation (1) indicate the early accelerating (homologously expanding) phase (blue line) with the timescale \(\tau\) and the later free expansion phase (approaching to a constant velocity; green line), respectively. This does not aim to mimic a specific astrophysical site (e.g., SNe or NS–NS mergers), but such types of temperature evolutions can be seen in many astrophysical environments \[21\]. The transition (intersection of the blue and green lines) is set at a constant temperature, \(T_t = 1 \times 10^8\) K (at \(t = t_t\)), which is below the transition point from the hot to cold r-process regime (\(\sim 5 \times 10^8\) K). This gives \(a = T_t/t_t^{-2/3}\) and \(t_t = \tau \ln(T_i/T_t)\). The multiplicable function in the second term of Equation (1) is \(f(t) = \ldots\)
FIGURE 2. Snapshot of nucleosynthesis when the neutron-to-seed ratio decreases to unity. The parameter set is taken to be \((S, \tau, Y_e) = (10, 10, 0.17)\). Experimentally known nuclear masses, \(\beta\)-decay rates, and neutron-capture rates are indicated by circles (white), crosses (green), and pluses (blue), respectively.

\[
0.5 - 0.5 \cos \pi(t/t_i) \quad \text{for} \quad t < t_i \quad \text{and} \quad f(t) = 1 \quad \text{for} \quad t \geq t_i.
\]

The temporal evolution of density \(\rho(t)\) can be obtained from the approximative adiabatic relation (with photons, electrons, and positrons) \([22, 19]\),

\[
S = 1.21 \frac{T_9^3}{\rho_5} \left( 1 + \frac{7}{4} \frac{T_9^2}{T_9^2 + 5.3} \right),
\]

where \(T_9 \equiv T/10^9 \text{ K}\) and \(\rho_5 \equiv \rho/10^5 \text{ g cm}^{-3}\).

NUCLEOSYNTHESIS

Nucleosynthesis calculations are performed for a wide range of parameter sets, \((S, \tau, Y_e) = (10–100, 10–100, 0.01–0.50)\) with the intervals of \((\Delta S, \Delta \tau, \Delta Y_e) = (10, 10, 0.01)\). Each calculation starts from \(T = T_i\) \((T_0 = 10)\) with the temperature and density temporal evolutions obtained from Equations (1) and (2). The initial compositions are taken to be \(1 - Y_e\) and \(Y_e\) for the mass fractions of free neutrons and protons, respectively. Rates for \((n, \gamma)\) and \(\beta\)-decay are taken from experimental results whenever available (e.g., [23]), and from theoretical estimates otherwise (Figure 2). For theoretical rates, the same nuclear masses based on the HFB-21 model [24] are utilized for both \((n, \gamma)\) [25] and \(\beta\)-decay [26] to maintain a consistency. This is important in particular for a cold r-process in which \((n, \gamma)\) and \(\beta\)-decay competes. Nuclear fission is not considered for simplicity.
Figure 3 shows $T$ (left-top), $N_n$ (right-top), $\tau_{n\gamma}/\tau_{\gamma m}$ (left-bottom), and $\tau_{n\gamma}/\tau\beta$ (right-bottom) as functions of time, where $\tau_{n\gamma}$, $\tau_{\gamma m}$, and $\tau\beta$ are abundance-averaged (for $Z > 2$) lifetimes for $(n, \gamma)$, $(\gamma, n)$, and $\beta$-decay, respectively. Red and blue lines indicate the results for the parameter sets $(S, \tau, Y_e) = (10, 100, 0.14)$ and $(10, 10, 0.14)$, taken as representative of hot and cold cases, respectively.

### hot vs. cold r-processes

In the hot case, the 2nd (square) and 3rd (circle) peaks form when the temperature is still high (top-left; $T_9 > 0.5$) owing to a long $\tau$ and thus the $(n, \gamma)-(\gamma, n)$ equilibrium approximately holds (left-bottom) all the way. In the cold case, however, both the peaks form when the temperature decreases below $T_9 = 0.2$ owing to a short $\tau$, resulting in $\tau_{n\gamma}/\tau_{\gamma m} \ll 1$ and a competition between $(n, \gamma)$ and $\beta$-decay (right-bottom). From this example we find that the expansion timescale $\tau$ is a key quantity for ramifications into hot and cold r-processes. Here, we define the critical value $\tau_{n\gamma}/\tau_{\gamma m} = 0.5$ that divides the hot ($> 0.5$) and cold ($< 0.5$) regimes.

The values $\tau_{n\gamma}/\tau_{\gamma m}$ versus $\tau$ at the 2nd (square) and 3rd (circle) peak formation are
plotted in Figure 4 for all \((S, \tau, Y_e) = (10, 10–100, 0.01–0.50)\). Here, entropy is fixed to \(S = 10\). We find that (i) for \(\tau > 30\), both peaks form in a hot r-process, (ii) for \(\tau \approx 20–30\), the second and third peaks form in hot and cold r-processes, respectively, and (iii) for \(\tau < 20\), both peaks form in a cold r-process. A cold r-process takes place only in rapidly expanding matter with \(\tau < 30\).

**overall abundance distribution**

The nucleosynthetic abundances for \((S, \tau, Y_e) = (10, 10/100, 0.01–0.50)\) averaged for all \(Y_e\) events with an equal weight are shown in Figure 5 (left), where \(\tau = 10\) and 100 represent cold (blue) and hot (red) cases, respectively. We find that both cases are similar for \(A < 140\), which are in reasonable agreement with the solar r-pattern (dots). This is
encouraging, in particular when we notice the presence of measured nuclear masses and $\beta$-decay rates relevant to the formation of high-$A$ wings of the first ($A = 80$) and second ($A = 130$) peaks (Figure 2). On the other hand, we find visible differences between hot and cold cases for $A > 140$. A better agreement for the cold case with the solar $r$-pattern can be seen, in particular near the third peak ($A = 195$). Note that, however, the result could be highly sensitive to the nuclear data of relevance ($A > 140$), for which no experimental information is available.

Right panel of Figure 5 shows the result of hot cases for $(S, \tau, Y_e) = (10/100, 100, 0.01–0.50)$, where $S = 10$ and 100 represent low (blue) and high (red) $S$ cases, respectively. We find remarkable differences for $A < 100$ between high and low $S$ cases, while those for $A > 140$ are similar. This is a consequence of the fact that the seed abundances are formed in nuclear statistical equilibrium (NSE) and quasi nuclear equilibrium (QSE) for the low ($S < 15$) and high ($S > 15$) cases, forming the abundance peaks (prior to the $r$-process phase; $T_9 \sim 4$) at $A \approx 80$ and 90, respectively [3]. A low entropy environment is thus needed for the formation of the 1st peak ($A = 80$) of the $r$-abundances. Hereafter, we consider the low entropy ($S = 10$) case only, which does not affect our discussion on the $r$-abundances beyond $A = 100$.

**high-mass wing of the 2nd peak**

As can be seen in Figure 2, there exist experimentally known data for nuclear masses and $\beta$-decay (but not neutron capture) rates relevant to the formation of the high-$A$ wing of the 2nd peak ($A = 130–140$; relatively close to the $\beta$-stability). Nucleosynthetic abundances should thus closely follow the solar $r$-pattern in this region, given that the solar $r$-distribution is “universal”. This is particularly true for a hot $r$-process, in which the abundance pattern hardly depends on $(n, \gamma)$ rates. Figure 6 (left) shows the calculated

**FIGURE 6.** Left: nucleosynthetic abundances for (non-averaged) parameter sets for cold (blue line) and hot (red line) cases $(S, \tau, Y_e) = (10, 10/100, 0.24/0.22)$, respectively, which form the high-$A$ wing of the 2nd peak. The solar $r$-abundances are scaled to match the 2nd peak height. Right: same as the left panel, but for the 3rd peak ($Y_e = 0.15$ and 0.14 for cold and hot cases, respectively). Dotted lines indicate the abundances before $\alpha$-decay.
abundances for single (i.e., non-averaged) parameter sets for cold (blue line) and hot (red line) cases \((S, \tau, Y_e) = (10, 10/100, 0.24/0.22)\), respectively. These are responsible for the formation of the high-\(A\) wing of the 2nd peak abundances. We find excellent agreement for both cases with the solar r-pattern in this region \((A = 130–140)\). This can be regarded as one of great achievements of nuclear experimental studies. However, this also means that we need experimental information beyond \(A = 140\) in order to distinguish cold and hot cases.

**high-mass wing of the 3rd peak and Pb**

As in the case of the 2nd peak, the high-\(A\) wing of the 3rd peak \((A = 195–205)\) can serve as a diagnostic to test cold and hot r-process conditions, for which future nuclear experiments of relevance may become feasible (relatively close to the \(\beta\)-stability). Figure 6 (right) shows the calculated abundances for cold (blue) and hot (red) cases that form the high-\(A\) wing of the 3rd peak, \((S, \tau, Y_e) = (10, 10/100, 0.15/0.14)\), respectively. We find visible differences between the cold and hot cases around \(A = 195–205\) with the former being in better matching to the solar r-pattern. Note, however, we cannot conclude the cold case responsible for the r-process, when considering no available experimental information relevant to this mass range. Future experimental studies for \(A = 195–205\) and \(N = 126\) (neutron magic number) will be crucial to elucidate the physical conditions for the r-process.

Also important are spectroscopic analyses of Pb abundances in r-enhanced Galactic halo stars [14]. The lowest metallicity stars ([Fe/H] \(\approx -3\)) show deficient Pb abundances (factor of 2 smaller than the “solar” r-value) [27, 28, 29, 30], although more metal-rich stars have higher values [31] (that could be affected from s-process contaminations). This indicates the Pb abundances in such stars being solely due to \(\alpha\)-decay from Th and U with negligible production of \(\alpha\)-decay progenitors of \(A = 210–230\) [27]. Note that the solar r-component of Pb abundance is quite uncertain [32] and the stellar Pb abundances (without s-process contaminations) should be more reliable. As can be seen in Figure 6 (right), a cold r-process leads to substantially smaller Pb abundances \((A = 206–208)\) than those in a hot case. This can be explained by the sizably smaller amount in the range \(A = 210–230\) (dotted line in the right panel of Figure 6) for the cold case, being a consequence of continuing capture of neutrons supplying by \(\beta\)-delayed emission during the freezeout phase (with the neutron-to-seed ratio less than unity). This does not happen in a hot r-process owing to a push back by photodisintegration.

**SUMMARY**

We explored the physical conditions for the r-process based on a site-independent model with time-evolving temperature and density. Nucleosynthetic calculations show that the abundance patterns for cold \((T_9 < 0.5;\) without photodisintegration) and hot \((T_9 \sim 1;\) with the \((n, \gamma) - (\gamma, n)\) equilibrium) r-process conditions can be distinguished only for \(A > 140\). This implies that future nuclear experimental studies relevant to the high-\(A\) wing of the 3rd peak \((A = 195–205\) and \(N = 126\)) will be crucial to elucidate the physical conditions...
for the r-process (see also discussion in [33] for the rare-earth region $A = 150–180$). Future spectroscopic analyses of Pb abundances in Galactic halo stars are also crucial to distinguish cold and hot r-process conditions.

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